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## THE STRENGTH OF THE EARTH'S CRUST

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#### INTRODUCTION AND SUMMARY

In Part I were examined certain geologic tests of the strength of the crust; in Part II the geodetic evidence in regard to the effective areal limits of rigidity; in Part III the influence of variable vertical distribution of density. All three lines of investigation converge toward showing the rigidity of the outer crust—the zone of isostatic compensation—to be such that very considerable stresses can be carried over areas whose radii range between 100 and 300 km. There arise to be considered next the following problems: first, the variability in depth of compensation and its influence; second,

whether the stresses represented by the incompleteness of isostasy are carried by the rigidity of the outer crust, or are transferred in some measure to the deeper body of the earth; third, the magnitudes of the stresses, measured in terms of loads, which are indicated by the gravity anomalies and deflection residuals.

It is found in answer that under the hypothesis which forms the basis of Hayford's work, that of uniform compensation, complete at a given depth, there are indications, given by comparing different areas, of a great range in the depth of the bottom. Under an assumption which is probably nearer to nature—that is, the hypothesis of a variable and gradually disappearing compensation—there is room for even a greater heterogeneity of the crust and a greater variability in the depth reached by the zone of compensation. But, on the other hand, it is concluded that the zone of compensation, as an outer rigid crust separated from the rigid inner earth by an intervening zone of lowered rigidity, is a reality in earth structure. The stresses due to the heterogeneities of density and relief within and upon this crust appear to be borne by the crust, not by the inner earth. Under the third subject it appears, upon review of the evidence given by the deflection residuals, that these may be interpreted so as to show departures from equilibrium comparable to the results given by the gravity anomalies, instead of the 250 feet which Hayford thought to exist. The two independent lines of geodetic investigation are thus seen to agree and it may be concluded with some confidence that the individual isostatic regions of the United States are on the average between 600 and 900 feet out of equilibrium. Evidence from other parts of the world appears to show, furthermore, that a number of regions exhibit greater departures from isostasy than those observed within the United States. The strain imposed on the crust by the Niger Delta, though large, is apparently not as large as some made known by geodetic measurements.

Thus from various directions of attack the crust is shown to be an earth shell of high rigidity and consequently high elasticity. Geodetic evidence justifies the view, brought forward by geologic evidence, that the delta of the Niger is to be looked upon as supported by the strength of the crust.

VARIABLE OR CONSTANT DEPTH OF COMPENSATION

The Cordilleran region awoke to an era of great orogenic and igneous activity near the beginning of the Tertiary, and, especially in the Neocene, has become broadly elevated into one of the great plateau regions of the world. Large areas like the Colorado plateaus, which since the beginning of the Paleozoic had rested near sea-level, at times beneath and again slightly above, have been lifted many thousands of feet. Block-faulted structures indicate the dominance of vertical forces rather than surficial compression as the cause of these movements. The uplift has not been of the nature of a broad even upwarp, and adjacent regions show great contrasts in elevation. These different surface results of the interior forces suggest differences in elevatory forces at comparatively shallow depths. The region is known to be in a fair degree of isostatic equilibrium notwithstanding the high relief. Davis has shown why these movements cannot be regarded as differential sinkings toward the center of the earth.[1] These features suggest, then, subcrustal decreases in density during the Tertiary as a cause of the broad movements of elevation.

The rising of great bodies of magma to high levels in the zone of isostatic compensation, their irregular distribution, the great quantities of heat and gases which would invade the roofs are suggested by the observed evidences of regional igneous activity at the surface as the probable causes of the changes in density and regional vertical movements. A consequence of such a cause would be a lessened strength of the crust to resist strain, a lessened depth to the zone of isostatic compensation, and a decreased size of the unit areas departing from equilibrium.

The history of the Cenozoic in the Cordillera has repeated the history of other regions at other times, either in the Archean igneous activity or later. The slow conduction of this excess heat from the outer crust, the solidification of the reservoirs of magma, would, in the course of ages, bring about a new rigidity. Upon disturbances of the equilibrium by erosion or compressive forces there would be found a new and greater depth to the zone of compensation.

[1] "Bearing of Physiography upon Suess's Theories Abstract," *Intern. Geog. Cong., 8th Report*, 1905, p. 164; *Amer. Jour. Science* (4), XIX (1905), 265–73.

Where ages of uplift and erosion have followed periods of igneous activity there are revealed great bodies of intrusive rock varying in density from granites at 2.65 to gabbros at 3.0. These great batholiths are of irregular distribution in the crust, both vertically and horizontally. Their abundance increases downward so far as erosion has revealed the evidence. The outer crust of the earth has become vertically and areally heterogeneous by such means and should cause variations and irregularities to an appreciable degree in the distribution of isostatic compensation, as noted under the topic of the influence of variable rate of compensation upon gravity anomalies. Here we note in addition the decreased depth of compensation and decreased rigidity at the time of intrusion.

Hayford notes that the stations classified into geographic groups show as a rule as great contradictions in depths of compensation between adjacent groups as in those which are far apart. This variation between adjacent groups is taken by him as weakening the evidence that there is any real variation in the depth of compensation over the whole area investigated.[1] For the reasons outlined previously, the present writer, influenced by the geologic inferences, does not view such irregularity of distribution as proof that the evidence is weak and conflicting. The strength of the evidence must be judged rather by the nature of the residuals. Hayford points out that the depth of compensation in the West seems on the whole to be somewhat less than in other parts of the United States, though he does not regard it as safe to assert that it does exist. On dividing the whole area into four sections, the minimum sum of the squares of the residuals indicates depths as follows as best satisfying the hypothesis of uniform distribution of compensation:

From all residuals of the central group, 174 km.
From all residuals of the northeastern group, 187 km.
From all residuals of the southeastern group, indeterminate.
From all residuals of the western group, 107 km.[2]

In the 1909 paper Hayford gives a tabulation of the residuals for fourteen geographic groups. The results for the United States as a

[1] 1909, pp. 58, 59. [2] 1906, pp. 142–46.

whole and for the groups showing the shallowest, deepest, and the most irregular compensation are quoted below.[1] That solution is regarded as nearest the truth which gives the smallest mean value of the squares of the residuals.

TABLE XIX

PROBABLE DEPTHS OF COMPENSATION

| GROUP | NO. OF RESIDUALS $\delta$ | MEAN VALUES OF THE SQUARES OF THE RESIDUALS IN VARIOUS GROUPS | | | | | MOST PROBABLE DEPTH |
|---|---|---|---|---|---|---|---|
| | | Solution B Infinite Depth | Solution E 162.2 Km. | Solution H 120.9 Km. | Solution G 113.7 Km. | Solution A 0.0 Km. | Km. |
| *United States* (all observations) | 733 | 146.50 | 14.05 | **13.73** | 13.75 | 25.77 | **122.2** |
| Group 12 (parts of Minn., N.Dak., S.Dak., Neb., Kan.) | 36 | 196.57 | **7.00** | 7.47 | 7.59 | 11.46 | **305** |
| Group 5 (Mich., Minn., Wis.) | 52 | 34.97 | **23.60** | 23.64 | 23.67 | 27.53 | 152 |
| Group 8 (parts of Utah, Nev., Cal.) | 42 | 128.97 | 22.27 | 18.79 | **18.25** | 35.78 | **66** |
| United States (residuals multiplied by 1.327 to compare with Group 8) | ..... | 194.40 | 18.65 | **18.23** | **18.25** | 34.21 | ..... |

It is seen that the mean value of the squares of the residuals in group 12 with most probable depth of 305 km. is considerably less than for the United States as a whole, in part no doubt owing to the moderate relief, yet the differences between the residuals in group 12 for the different solutions is much more pronounced than for the United States as a whole. The number of stations, 36, is large enough so that this can hardly be regarded as accidental. On the contrary, it would appear that for the whole United States the group differences are sufficient to mask in part the accuracy of the mean result of 122 km. and that the depth of compensation within certain groups is more reliable than for the United States as a whole.

In group 8 with most probable depth of 66 km. the mean value of the squares of the residuals is nearly 50 per cent higher than for

[1] 1909, pp. 55–58.

the United States as a whole, a value which may be ascribed to the mountainous relief and the support of individual mountains and ranges by the rigidity of the crust. Nevertheless the residuals for the several solutions fall into a somewhat regular system, and solutions E, H, and G are more sharply differentiated from the most probable one than for the whole United States. They may be compared better with the latter if the residuals for the whole country are multiplied by 1.327 as a factor in order to give the same numerical value under solution G. This is done at the bottom of the table. It would appear from these figures as though the arguments previously given from geologic analysis receive considerable support from the geodetic results and point to a much shallower depth for isostatic compensation in the Great Basin than over certain other portions of the United States. Furthermore, in the examination of the question of local versus regional compensation, it was only the forty mountain stations classified into two groups according to elevation which gave any suggestion that regional compensation to a radial distance of 166.7 km. was not about as probable as more local compensation. In these two lines of geodetic evidence as to limited depth and breadth of compensation there are suggestions therefore which support the geologic inference that the crust of the Cordilleran region may be weaker than over the United States as a whole. On the other hand, the warping or faulting-down of ancient continental areas into marginal sea-bottoms implies an increasing density of the subcrust and therefore possibly an increasing rigidity and strength under such areas. Such a contrast between the Atlantic Ocean bottom and the Great Basin would correspond to the great strength of crust necessary to sustain the delta of the Niger as compared with the moderate rigidity found by Gilbert for the crust beneath extinct Lake Bonneville, located within the limits of group 8.

The regions of shallower compensation in the United States are on the whole marked probably by a higher temperature gradient, the regions of deep compensation by a lower. This is illustrated by the very high gradient of the Comstock mine in Nevada and the very low gradient which is found in the Lake Superior copper mines. The temperature gradient may measure the depth to a zone of low

rigidity, determined by a certain relation of temperature and pressure.

Within an overlying zone of high rigidity, even where it is of uniform depth, the geodetic measurements of the depth of compensation may not, however, show uniformity. If the density is unequally distributed, the compensation of a region may be nearly completed at some depth above the base of the rigid zone, the lower part consisting of rock of mean density and therefore not possessing influence. A region of deep and marked rigidity, if characterized by notable irregularities in the distribution of either density or relief, would show large residuals. A region characterized by more uniform distribution of density and gentle relief would show lower residuals even with the same rigidity. A region with deep compensation would show within the limits of the group lower residuals for the same degree of uniform compensation, than where compensation was at lesser depths, since the attracting masses are spread over a greater distance.

As applications and tests of these principles, it is to be noted that group 5, embracing the Lake Superior region with its low-temperature gradients, has the highest residuals of any group in the United States. Further, the mean values of the least squares for the different solutions show less differentiation than in any other group. These facts suggest irregular distribution of density, high rigidity, and the zone of rigidity may extend below the most probable depth, 152 km., indicated for the limits of compensation. The topographic deflections are only 58 per cent compensated. The contiguous group to the southwest, No. 12, shows the lowest residuals of any group, the separate solutions are sharply differentiated and the depth is the greatest in the United States. On the side of this area, the gravity anomaly at St. Paul, 0.059 dyne per gram, is, next to Seattle, the largest found thus far in the United States. It may be concluded, then, that in this part of the continent, undisturbed by igneous activity or mountain-building since the pre-Cambrian, the depth of the zone of rigidity appears to be very great. The irregularities in residuals in group 5 may date from the Keweenawan period, when enormous masses of basic and therefore heavy magmas were intruded and extruded in the Lake

Superior region. If such be the case it shows the long endurance of strains borne by this part of the earth. In the almost universal epeirogenic movements which marked the close of the Tertiary and opening of the Pleistocene, the Lake Superior basin showed notable downwarping, its bottom being now beneath the level of the sea. It formed a trough which directed the flow of glacial ice. The latter must have scoured it clean but can hardly be ascribed as the cause of the existence of the basin. The crust movements have doubtless been in the direction of relief of stress, but the relief has been but partial; geodetic investigation reveals that the age-long load is yet borne.

### DEPARTURES FROM ISOSTASY SUSTAINED BY RIGIDITY IN THE ZONE OF COMPENSATION

It was concluded under the last topic that the rigidity over certain parts of the earth probably carries the zone of possible compensation as deep as 300 km. even under the assumption of uniform rate, an assumption which tends to minimize the depth; whereas in other regions under that hypothesis it is less than 100 km. in depth. This raises the question whether the regional departures from isostasy are carried as strains within the zone of compensation or are transferred in part to the deeper body of the earth. There are reasons for believing that the former is the case, pointing by inference to a zone of markedly diminished rigidity between the rigid lithosphere and still more rigid centrosphere.

The geodetic evidence consists in the large values of the squares of the residuals for solution B, the solution which postulates extreme rigidity and compensation at infinite depth. For the whole United States, as shown in the Table XIX, p. 293, the mean value of the squares of the residuals for solution B is 10.7 times the value for solution H. But for group 12, that for which the most probable depth of compensation is 305 km., the distinction is still greater; solution B showing a mean-square residual 28 times greater than for solution E. Dividing in this way the value for solution B by the value for the most probable solution, and taking the mean for all those groups which indicate a depth of compensation greater than the average for the United States, it is found that the ratio is twice

as great for the groups with deep compensation as for the United States as a whole. That is, the groups with deep compensation, instead of showing a leaning toward solution B show on the contrary more definitely that it is not true. The hypothesis of uniform compensation complete at a certain depth appears to be more nearly true for regions with deep compensation than for shallow compensation. This does not mean, however, a lesser rigidity of the crust for the regions with deep compensation, their high capacity to carry strain being shown by the large gravity anomalies which are found in places within them.

There seems to be no evidence, however, that the zone of diminished rigidity is sharply bounded or is marked by real liquidity. It is doubtless due to the gradual rise of temperature with depth, overcoming within a certain zone the influence of the increasing pressure. Seismologic and tidal evidences show, furthermore, that under stresses of relatively brief duration the earth acts as a unit and as an elastic rigid body. The physical condition of the zone of low rigidity may approach that of a highly viscous fluid, the time element thus entering within these limits as a fundamental factor. This zone is incapable of bearing pronounced strains for long periods in the manner of the zone above. In geologic operations it thus serves to separate the mode of expression of forces generated below from those originating above this level. The former give rise to the great compressive movements in the outer zone, the latter to the vertical movements not determined by tangential compression.

### INTERPRETATION OF DEFLECTION RESIDUALS IN TERMS OF MASSES

On p. 59, paper of 1909, Hayford shows that the actual deflections of the vertical average only one-tenth of what they would be if the continent and the portions of the ocean basins which were included in the calculations were both underlain by matter of the same density and the relief sustained wholly by the rigidity of the crust. The effect of the topography calculated on this assumption —that the density is uniform and the larger as well as the smaller features are sustained by rigidity—gives what is known as the topographic deflections. These, as stated above, average ten times

the value of the actually observed deflections. The surface may be regarded, therefore, as nine-tenths compensated by variations of density. The details for the five more significant groups are given below:[1]

TABLE XX

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|
| No. | Area of Group | No. of Stations in the Group | Probable Depth of Uniform Compensation in Kilometers | Mean of Topographic Deflections without Regard to Sign | Mean Residual of Solution H without Regard to Sign | Value in Sixth Column Divided by Value in Fifth Column | Percentage of Completeness of Isostatic Compensation for Solution H |
| 12.... | Parts of Minn., N.Dak., S.Dak., Neb., Kan..... | 36 | 305 | 8.23 | 2.17 | 0.26 | 74 |
| 8.... | Parts of Utah, Nev., Cal.... | 42 | 66 | 32.23 | 3.57 | .11 | 89 |
| 10.... | Cal., southern part..... | 57 | 126 | 65.44 | 3.91 | .06 | 94 |
| 9.... | Cal., northern part..... | 60 | 176 | 60.50 | 2.93 | .05 | 95 |
| 14.... | Northern Cal., western Ore., and Wash..... | 37 | 84 | 53.68 | 3.37 | .06 | 94 |
| | Whole United States..... | 733 | 122 | 30.37 | 2.91 | 0.10 | 90 |

Group 12 gives the greatest depth for uniform compensation. By using the residual for Solution E, 2.09, the percentage of completeness of compensation would have been 75, a trifle more than for Solution H, but still next to the least perfect in the United States.

Group 8, the Great Basin region, has the lowest depth of compensation but shows about the average approximation to isostatic equilibrium.

Groups 10, 9, 14 comprise the Pacific Coast Ranges. They give the highest topographic deflections of the United States, doubtless on account of the great relief of the ocean basin and continental border, but the actually observed deflections do not differ greatly from group 8 or the mean for the whole United States. The result is that in this mountain region bordering the continent the degree

[1] Taken from pp. 56, 58, 69, and illustration No. 2, Hayford, 1909.

of completeness of compensation is the highest in the United States.

On the basis of the figures for the whole United States Hayford writes: "The average elevation above mean sea-level being about 2,500 feet, this average departure of less than one-tenth from complete compensation corresponds to excesses or deficiencies of mass represented by a stratum only 250 feet (76 meters) thick on an average."[1] It is this last statement, interpreting the deflection in terms of mass, which has meaning to the geologist. It has been widely quoted as perhaps the chief geologic result of the work and yet the writer believes that it is without basis. By an oversight of the author he misinterprets his results. If the present writer is correct in making this statement it should not be taken, however, as a criticism of the mathematical portion of the work.

The sea-level is from the standpoint of the problem of isostatic compensation but little more than a datum surface. Imagine the ocean water to be converted into rock of density 2.7 of the same mass as the water and resting on the present ocean bottom. Every thousand feet of water would be replaced by 380 ft. of rock. Then the sea-level surface after this transmutation is seen to lose all real significance.[2] To show the fallacy of taking this level as a basis for interpreting the departures from compensation in terms of thicknesses, let attention be given to groups 1, 2, 3, 4, 6, 11,[3] which cover the United States east of the Mississippi River. The average departure of these from compensation is 0.11, which on the basis of Hayford's statement means that the surface on the average departs but 275 ft. from the level which would give complete isostatic equilibrium on the hypothesis of uniform distribution of compensation to a depth of 122 km. If, however, this eastern third of the United States be regarded by itself, its average elevation may be assumed as 1,000 ft. (it is probably less). By the same reasoning as Hayford applied to the whole United States, 11 per cent of this is 110 ft. Therefore although the average deflections are slightly

[1] 1909, p. 59.

[2] More accurately, the equivalent rock should be imagined as suspended at the mean depth of the water, but the effect of the difference in level is negligible upon the topographic deflection.

[3] 1909, p. 59.

greater than for the United States as a whole, it would be concluded that for the region east of the Mississippi the departure from the levels giving complete compensation averages not more than 110 ft. instead of the 275 ft. previously stated.

Or, again, imagine a rise of ocean-level so that the average elevation of this part of the continent is reduced to 100 ft. without changing the detail of the topography. The deflections would suffer only small alterations due to the added mass of water. Although the crust remained without change, the same reasoning would then lead to the conclusion that the topography departed on the average but 11 ft. from the levels which would give complete compensation.

In computing the influence of the topographic irregularities and their compensation upon the deflection of the vertical, all the topography was taken into account up to a radial distance of 4,125 km. from each station. This radius is approximately the length of 37° of latitude. It embraces the Pacific Ocean out to the Hawaiian Islands and to ten degrees south of the equator, and the Atlantic Ocean out to the Azores. The relief within this region ranges from −8,340 m. north of Porto Rico to +6,220 m. in Mount McKinley, +6,247 in Chimborazo; a total differential relief of about 14,590 m. About one-half of the topography surrounding the coast stations consists of ocean bed. Even for the stations in Minnesota, farthest removed from the sea, about one-third of the surrounding topography within the limits is deep ocean, but lying at a greater distance and carrying lesser influence. The average depth of the oceans influencing the deflection of the station at mean distance inland may be assumed for purposes of illustration to be about 5,000 meters. This depth of water is equivalent in mass to 1,900 m. of rock of density 2.67, leaving an effective ocean depth of 3,100 m. Add the mean continental elevation of 760 m. to this, and 3,800 to 3,900 m. represents about the effective mean relief between continent and ocean. On coast stations this differential relief has greatest influence. For inland stations the several portions of the continent have proportionately more effect. For the United States as a whole it is this relief of between 3,500 and 4,000 m. between continent and ocean, more than the relief between the major features of the continent, which is nine-tenths compen-

sated by the corresponding variations in crustal density, not the 760 m. which is the average elevation of the United States above sea-level.

It is the belt of Pacific coast stations which measures more closely than other groups the degree of compensation accompanying the continental relief above the ocean bottoms. These stations lie in groups 10, 9, and 14, for which the mean residuals are but 0.06, 0.05, and 0.06 of the mean topographic deflections respectively. These residual deflections indicate that for this coastal zone the departures from complete compensation amount to but 5 or 6 per cent. If the mean effective relief which controls this be assumed as 4,000 m., then the mean departure from equilibrium is represented by a mass 200 to 240 m. thick, approximately between 650 and 800 ft. On the other hand, groups 5 and 12 are those farthest removed from the ocean basins and their deflections are controlled most largely by the internal continental relations. For them the departures from complete isostatic compensation as measured by the ratio of the mean residuals to the computed topographic deflections amount to 42 and 26 per cent. The mass to which this is equivalent may be no greater than the 5 per cent departure on the Pacific coast. These estimates fall into the same order of magnitude as that of the masses represented by the gravity anomalies.

This reconnaissance of the problem is sufficient for present purposes. It is readily seen that even greater difficulties stand in the way of a precise statement regarding the equivalence of mass corresponding to deflections of the vertical than arose in the interpretation of the gravity anomalies. The residual for each observed deflection is the sum of the influences of all the excesses and deficiencies of mass as compared to solution H on all sides of a station. The effect of each unit varies inversely with the square of the distance and directly with the sine of the angle which the line of force makes with the horizontal passing through each station. A combination of the data from the measurements of the intensity of gravity with those of the deflections of the vertical would apparently be necessary to state for each region the equivalence in terms of mass which is implied by the residual at each station.

MAXIMUM LOADS INDICATED BY ANOMALIES

Hayford and Bowie consider that 0.0030 dyne of anomaly may be regarded as equivalent to 100 ft. of rock possessing a density of 2.67. From the previous considerations it would seem that this is probably too high for a mean figure, but may apply to certain areas, especially those with extremely broad boundaries. In other regions 0.003 may be far too high, since it is shown under the topic "Variable or Constant Depth of Compensation" that in certain parts of the United States the depth of the zone of compensation probably goes notably deeper than in other parts and the density may be distributed either nearly uniformly or with considerable irregularity. The greatest depth of compensation indicated for any region is 305 km. A unit thickness of mass uniformly distributed to this depth and to a radius of 166.7 km. would give but 0.0014 of anomaly instead of 0.0024 as given by a depth of 114 km., or 0.0030 as taken by Hayford and Bowie. For general use 0.0024 dyne is perhaps the best value, corresponding to a uniform distribution of a unit excess or defect of mass to a depth of 114 km. and to a radial distance of 166.7 km. For the mean anomaly of 0.018 this would give 750 ft. of elevation as the mean departure of the surface of the United States above or below the position giving isostatic equilibrium, instead of 600, or more exactly, 630 ft. as taken by Bowie. The largest known anomaly in the United States is at Seattle, −0.093. This corresponds to a defect in mass equivalent to a stratum 4,000 ft. thick if the divisor is 0.0024, a stratum 3,200 ft. thick if the divisor is 0.0030. At Olympia, but 50 miles or 80 km. distant, the anomaly is +0.033, corresponding to excesses of mass of 1,375 or 1,100 ft., according to the divisor. The difference of regional load between Olympia and Seattle becomes 5,375 or 4,300 ft.

But these relations of unit thickness of mass to the gravity anomaly are based on the assumption that the excess or deficiency of mass extends to as great a radial distance as 166.7 km. radius. This minimizes the thicknesses or densities needed to account for the anomalies above what would be required for a more local concentration of mass. But an inspection of the distribution of gravity and deflection residuals shows that in many cases the masses

producing the greater disturbances have much smaller size. This is especially striking in the case of the largest negative anomaly in the United States, that at Seattle, only 50 miles from the large positive anomaly at Olympia. The latter is surrounded on all sides by negative anomalies as follows:

DISTANCES FROM OLYMPIA, WASHINGTON

| | | | |
|---|---|---|---|
| Astoria, Ore..... | 76 miles | S.W. | −.013 dyne anomaly |
| Heppner, Ore..... | 195 " | S.E. | −.027 " " |
| Skyhomish, Wash.. | 84 " | N.E. | −.028 " " |
| Seattle, Wash. .... | 50 " | N.N.E. | −.093 " " |

The excess of mass which exists in the vicinity of Olympia, above that required for compensation under solution G, must therefore be much less than 166.7 km. (102.5 miles) in radius. The same is doubtless true of that excessive deficiency which exists at Seattle, since the anomaly sinks to less than one-third the value at Skyhomish only 45 miles east, and changes to a large positive anomaly at Olympia, 50 miles south-southwest.

The large positive mass in the vicinity of Olympia must diminish appreciably the effect of the still larger negative mass in the vicinity of Seattle. The latter with the other surrounding negative masses must diminish still more the anomaly due to the positive mass at Olympia. Furthermore, it is highly improbable that the observations at Seattle should happen to be made at the point of really maximum anomaly. Let the very moderate assumption be made then that the abnormal Seattle mass as a unit by itself would give a maximum anomaly of −0.100 dyne. It would doubtless give more. Let limiting assumptions be made as to the dimensions and density of this mass such that the actual volume and density are quite probably embraced somewhere within these limits. Tables XXI[1] and XXII show the results of such assump-

[1] Table XXI is readily derived from Table X, Part III. Take, for example, the cylinder of radius 1,280 meters, depth of 1,000 feet, and density 0.267. Multiply its dimensions by 30 and the volume of each unit portion will be increased by the cube of 30. The attraction of each unit of mass on the given point will vary inversely with the square of the distance and will therefore be diminished by the square of 30. The anomaly will consequently increase directly with the dimensions, provided that the density remains constant. This gives the basis for the calculations in column 2, Table XXI.

tions. In Table XXI the attracting mass is supposed to have the form of a vertical cylinder. With a given anomaly the deficiency

TABLE XXI

VERTICAL CYLINDERS GIVING A NEGATIVE GRAVITY ANOMALY OF 0.100 DYNE AT CENTER OF TOP SURFACE OF CYLINDER

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| Diameter | 76.8 km. | 51.2 km. | 102.4 km. | 51.2 km. |
| Depth | 9.15 km. | 30.5 km. | 61.0 km. | 61.0 km. |
| Density | − 0.31 | − 0.15 | − 0.07 | − 0.12 |
| 2.80 − Density | 2.49 | 2.65 | 2.73 | 2.68 |
| Thickness of cylinder of same area and mass, but density 2.67 | 1,080 m.<br>3,550 ft. | 1,700 m.<br>5,600 ft. | 1,700 m.<br>5,600 ft. | 2,770 m.<br>9,080 ft. |
| Anomaly per 100 feet of mass of density 2.67 expanded to depth of cylinder as given in second line | 0.0028 dyne | 0.0018 dyne | 0.0018 dyne | 0.0011 dyne |

TABLE XXII

SPHERES GIVING A NEGATIVE GRAVITY ANOMALY OF 0.100 DYNE AT POINT VERTICALLY ABOVE ON THE SURFACE OF THE EARTH

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| Diameter | 50. km. | 100. km. | 50. km. | 100. km. |
| Depth to center | 25. km. | 50. km. | 32. km. | 64. km. |
| Density | − 0.144 | − 0.072 | − 0.236 | − 0.118 |
| 2.80 − Density | 2.66 | 2.73 | 2.56 | 2.68 |
| Length of polar axis of oblate spheroid of same equatorial section and same mass, but density 2.67 | 2,700 m.<br>8,850 ft. | 2,700 m.<br>8,850 ft. | 4,420 m.<br>14,500 ft. | 4,420 m.<br>14,500 ft. |
| Anomaly per 100 feet of polar axis of mass at density 2.67 if expanded to diameter of sphere | 0.0011 dyne | 0.0011 dyne | 0.0007 dyne | 0.0007 dyne |

of mass will be least if the cylinder extends from the station downward instead of being at a greater depth. Furthermore, for a given volume and density of cylinder the gravitative force will vary according to the ratio of the depth to the diameter.

Let $H$ = depth
Let $2R$ = diameter
Let $F$ = gravitative force

Then $\pi R^2 H$ = the volume, a constant. To find the ratios of $H$ to $R$ which give maximum attraction for unit mass

Let $R^2H = 1$ and solve for various values of $R$ the equation

$$F = 2\pi\rho\gamma\left[\frac{(R^3+1)-1\sqrt{R^6+1}}{R^2}\right].$$

Several solutions are as follows:

For $H=0.75$, $R=1.15$; $F=(2\pi\rho\gamma)\ 0.523$
$H=1.00$, $R=1.00$; $F=(2\pi\rho\gamma)\ 0.586$
$H=1.50$, $R=0.81$; $F=(2\pi\rho\gamma)\ 0.609$
$H=2.00$, $R=0.71$; $F=(2\pi\rho\gamma)\ 0.586$
$H=4.00$, $R=0.50$; $F=(2\pi\rho\gamma)\ 0.200$

This shows that the gravitative force is a maximum for a cylinder of constant volume and mass in which the depth varies from one-half the diameter to four-thirds the diameter. The force varies but slightly between those limits. The cylinders of columns 3, 5, and 6, of Table XXI, lie within these limits. Thus all the assumptions thus far made favor the minimization of the negative load which produces the Seattle anomaly.

Taking the mean density of the outer part of the lithosphere as 2.80 it is seen that the cylinder of column 2, Table XXI, has a density below that of the lightest rock-making minerals and would require the existence of a molten magma or of abnormal pore space to great depth. It may therefore be eliminated as not probable. Cylinders 3, 4, and 5 show densities within the limits of granite, the lightest of the abyssal igneous rocks. It may be concluded, therefore, that the deficiency of mass, if of approximately cylindrical form, is equivalent to a negative load of between 5,000 and 10,000 feet of rock, extending over a distance of from 50 to 100 km., or a somewhat less local load superposed upon a broad but small regional load of the same sign. The nature of the assumptions has been such that we may conclude with confidence that the Seattle anomaly corresponds to at least 5,000 feet of rock and may reach a considerably higher figure, perhaps 10,000 feet. Furthermore, Hayford's unit mass, extending to the areal limits, 100 feet thick and density 2.67, would here produce an anomaly as low as between 0.0010 and 0.0020 dyne.

Instead of a cylinder suppose the mass which produces the deficiency of gravity to approximate more to the form of a sphere. The results are shown in Table XXII. In columns 2 and 3 the sphere is tangent to the surface, a position diminishing the mass for a given anomaly. In columns 3 and 4 the top of the sphere is 7 and 14 km. deep respectively. The low density of column 4 shows it to be beyond the limiting conditions. The load, though negative in sign, is seen to be equivalent in order of magnitude to the greater volcanic piles; 30 to 60 miles in diameter, 9,000 to 14,000 feet in height for rock of density 2.67. The anomaly produced by the unit mass of 100 feet thickness and density 2.67, considered here as 100 feet of polar diameter for a spheroid of the given horizontal dimensions, ranges between the low values of 0.0007 and 0.0011 dyne.

From a consideration of these two tables it is seen that the large anomalies require either a variation of mass equivalent to as much as 5,000 feet of rock extending over some thousands of square miles or to 10,000 feet of rock, more or less, extending over 1,000 square miles, more or less. These tables determine the order of magnitude, but the data are not sufficient to permit a more accurate solution of the problem.

Thus this detailed examination of the anomalies in the region of Seattle shows that the divisor of 0.0030, as taken by Hayford and Bowie, or 0.0024, as considered here the best for general use, is too high for the more limited areas of high anomaly. The latter may be regarded as made up in part of a regional portion for which the divisor of 0.0024 would be applicable and a local portion for which the divisor is probably not over 0.0015. As a mean value, for the more limited areas of large anomaly the amount due to the unit thickness of 100 feet of rock of density 2.67 should apparently not be taken as over 0.0020 dyne.

In forming conceptions as to the uncompensated vertical stresses existing widely in the earth's crust it is important to know the maximum range of departures from the mean stress as well as the latter. These can be studied well in Fig. 5.[1] The mean of fourteen maxima of defect of gravity is −0.033, the mean for eleven

[1] Fig. 5, p. 153, Part II; also see Hayford and Bowie, pp. 107–8.

areas of excess of gravity is +0.034. With the exception of the Seattle stations with an anomaly of −0.093, none reach a value of 0.060. It is thus seen that the average notable maximum is not far from twice the mean anomaly. Even by using a uniform divisor of 0.0024 or 0.0030 to convert anomalies, regional departures of load amounting to 1,300 or 1,500 ft. over areas of several square degrees are found to be not uncommon. Over smaller areas the loads rise to about three times the mean, and at Seattle to five times the mean. These figures of course do not measure simply the elevations or depressions of uncompensated erosion features. On the contrary, if the hills and valleys be imagined as smoothed out, then the resulting mean surface would be out of isostatic equilibrium in the same direction over distances amounting frequently to hundreds of kilometers and attaining maximum departures too low or too high over smaller areas by these figures.

But an inspection of the contour map of gravity anomalies (Fig. 5) shows that the large anomalies, those of 0.040 dyne or above, are all located by Hayford and Bowie as centers of maximum anomaly, though the nearest adjacent stations average as much as 100 miles distant. Between the widely spaced stations, the anomaly gradients are gentle. But where the stations form a series closer together, as that from the city of Washington to New York City, the gradients are seen to be steeper and more irregular. It is to be presumed that a further multiplication of stations would show increased complexity over the whole country and reveal maxima higher than those now recorded. The value of the mean anomaly without regard to sign should furthermore increase somewhat through the discovery of additional areas of maximum value. Areas of regional positive or negative anomaly would persist in something of their present size, but within broad areas of anomaly of one sign should be discovered smaller areas of opposite sign which are now unknown. Upon the completion of such a detailed survey the high anomaly of Seattle would not appear so exceptional as it does at present.

The chart of the residuals of Solution H[1] shows within the larger areas of like deflection of the vertical many large and sharp

[1] Illustration No. 3, Hayford, Supplementary Paper, Bowie, Illustration No. 5.

variations in value and in direction. The resultants of the plotted arrows point toward the centers of exceptional mass and their rapid changes in value and direction point toward the existence of many comparatively shallow masses. The epicentral points above such masses are those where the gravity anomaly, $Fv$, is at a maximum. If a hidden mass may be regarded as approaching a spherical form and has its center at depth $D$, the following relations exist between the value of the gravity anomaly and the distance $x$ from the epicenter:

$Fv$ = Maximum for $x = 0.00\ D$
$Fv = .75$ max. " $x = 0.46\ D$
$Fv = .50$ max. " $x = 0.77\ D$
$Fv = .25$ max. " $x = 1.23\ D$

If, for example, an approximately spherical mass has its center at a depth of 32 km., .005 of the earth's radius, the anomaly $Fv$ will fall to half-value at a distance of 25 km. from the epicenter. If the center is 64 km. deep, the anomaly will fall to half-value at 50 km. from the epicenter. Between stations located 100 km. apart by far the greater number of real maxima would be missed, and in so far as they depended upon masses in the upper half of the zone of compensation the indicated maxima would at most places be less than one-half the real maxima.

The stresses acting within the crust owing to excesses or deficiencies of mass are not so concentrated and therefore not quite so great as if those abnormalities of mass existed as surface loads of rock of density 2.67 in the manner imagined for the interpretation of anomalies.[1] Nevertheless to gain a conception of the meaning of the gravity anomalies, imagine the present compensated topography to be smoothed out to sea-level and the variations of mass away from isostatic equilibrium to become variations of volume upon its surface. The anomaly contours will then become topography contours, the line of zero anomaly will become the datum plane. The values in mass to be assigned to the successive anomaly contours can only be given in mean figures. It has been shown however in Part III that balanced vertical irregularities of density

[1] The relations of mass and its distribution to the resulting stresses will be considered in a later part.

do not play a large part in causing gravity anomalies. It will be shown later that neither can nucleal heterogeneity below the 200 to 300 km. level of isostatic compensation account for a large part. The anomalies represent in greater part real departures from isostasy and, as shown in this section, the limited areas of high anomaly are to be interpreted as implying on the whole a local load in higher ratio to anomaly than do the broad areas of anomaly. The average relation thought to exist is shown then in the following table:

TABLE XXIII

AN ESTIMATED AVERAGE RELATION OF ANOMALY CONTOURS TO CONTOURS OF EQUIVALENT ROCK MASSES OF DENSITY 2.67

| Anomaly Contour, Positive or Negative | Assumed Divisor for 100 Feet of Rock upon a Level Surface | Equivalent Contour in Feet, Positive or Negative |
|---|---|---|
| .020 | .0025 | 800 |
| .040 | .0023 | 1700 |
| .060 | .0020 | 3000 |
| .080 | .0018 | 4500 |
| .100 | .0016 | 6300 |

Upon conversion of a detailed anomaly map, if such existed, into the equivalent topographic contour map by means of such ratios as those given in Table XXIII, the whole United States with its compensated topography previously smoothed out to sea-level would be reconverted into a roughly mountainous country with no notable distinction between what are now the central plains and mountainous border regions of the continent. On to broad plateaus or basins upward of 1,000 feet from the mean elevation would be added higher elevations and depressions. The extreme differential relief would probably be in the neighborhood of two miles though the average departure without respect to sign from the mean surface of the geoid would probably be between 800 and 1,000 feet. Though everywhere as irregular as a mountainous country, there would be little or no relief of the mean level of this hypothetical surface above the ocean bottoms and no such broad and high masses as the Cordilleran plateaus would remain within

its limits. The major relief of the continent above the ocean bottoms would be about nine-tenths eliminated and the mean elevation of all areas as great as several hundred miles in width would be reduced to a small figure. This is the effect of isostasy. But within these unit areas which measure the limits of regional compensation would everywhere rise a rolling mountainous surface.

Imagine the hypothetical surface as broad as the United States, concealed from view by an impenetrable envelope of cloud, and aerial explorers to sink a sounding line to this invisible land at 124 places chosen at random. The resulting contour map compiled from these soundings would yield a much smoothed and flattened surface such as is shown in the contour map of gravity anomalies. Many of the soundings taken really on mountain slopes, because they were the highest of those made, might be casually interpreted as located on mountain peaks. The latter, standing sharp and high, would be missed save for an occassional lucky chance of the sounding line.

Interpreted in terms of weights and stresses, it is seen that even the parts of the continent appearing to the eye as plains long in geologic quietude really conceal within them strains as great as those imposed by the weight of mountains. That these great strains have been born for geologic ages, in many localities probably from the Archeozoic, gives a surprising conception of an enduring rigidity and elasticity of the crust wholly at variance with certain current doctrines regarding the weakness of this zone. It is not here found to be a failing structure.

On p. 81 Hayford and Bowie give the new-method anomalies for sixteen stations not in the United States. An abstract is given below of the greater anomalies from that table with the addition of Seattle. The thickness of stratum taken as corresponding to the anomaly is also added. This thickness, if the compensation is uniform with depth, measures the distance by which the earth's surface is out of isostatic equilibrium at those points. A plus sign indicates an excess of mass and a consequent tendency to sink, resisted by rigidity; a minus sign a defect of mass and therefore the existence of an upward strain.

The divisor 0.003 dyne of anomaly, taken as the equivalent

of 100 feet of abnormal mass of density 2.67, is Hayford's figure. As previously discussed it is thought to minimize too much the thickness of equivalent rock. It is given, however, for comparison with the column derived from the use of 0.0024 as a divisor. This is regarded as a better average figure, but for some cases at least, as shown for Seattle, this also may give too low a result.

TABLE XXIV

| Number and Name of Station | Elevation in Meters | New-Method Anomaly | Thickness of Equivalent Stratum on Land in Feet | |
|---|---|---|---|---|
| | | | 0.003 Anomaly = 100 feet | 0.0024 Anomaly = 100 feet |
| 2. Tonga plateau, Hecker, at sea | −2,700 | +0.255 | +8,500 | +10,625 |
| 4. Tonga deep, Hecker, at sea | −6,500 | − .184 | −6,130 | − 7,660 |
| 9. Mauna Kea, Hawaiian Islands | +3,981 | + .183 | +6,130 | + 7,660 |
| 10. Hachinohe, Japan | + 21 | + .110 | +3,670 | + 4,590 |
| 13. Sorvaagen, Norway | + 19 | + .146 | +4,870 | + 6,090 |
| Seattle, United States | | −0.095 | −3,170 | − 3,960 |

It is seen that the excesses of mass indicated for Mauna Kea and at Sorvaagen are each comparable in equivalent thickness and extent to the maximum thickness of the Niger Delta if measured by rock upon land, 5,450 feet. The departures from equilibrium at Hachinohe, Japan, and Seattle, United States, are comparable in thickness and area to the burden of the Nile Delta, the weight in air of 3,600 to 4,200 ft. of rock. In weight as in area, therefore, these deltas are seen to impose burdens on the crust no greater than are found, by means of geodetic observations, to exist in certain other regions where geologic evidence had not revealed them. The accuracy of Hecker's method for determining the intensity of gravity at sea has been called into question by Bauer[1] so that, until

[1] "On Gravity Determinations at Sea," *Amer. Jour. Science* (4), XXXI (1911), 1–18. "Hecker's Remarks on Ocean Gravity," *Amer. Jour. Science* (4), XXXIII (1912), 245, 248.

this question is settled by geodesists, equal weight should perhaps not be attached to the figures given for the departures from isostasy shown over the Tonga plateau and Tonga deep. Neither is the area of these departures known, though the areas of the plateau and deep are large. These regions are seen, however, to indicate considerably higher departures from isostasy than the measurements determined from the deltas of the Nile and Niger. The latter, therefore, perhaps do not measure the full strength of the crust.

Major H. L. Crosthwait has applied Hayford's methods to the investigation of isostasy in India.[1] The residuals of the deflections of the vertical serve as a measure of the degree of compensation existing in the United States as compared in India and are as follows:

UNITED STATES OF AMERICA

| | |
|---|---|
| Group S.E., mean residual | − 0".74 |
| Group N.E., mean residual | − 1.04 |
| Group Central, mean residual | − 1.66 |
| Group W., mean residual | − 4.02 |

INDIA

| | |
|---|---|
| Region No. 1, Himalaya Mountains, mean residual | −16".7 |
| Region No. 2, Plains at foot of Himalaya Mts., mean residual | − 2. |
| Region No. 3, N.E., mean residual | + 8. |
| Region No. 4, Central, mean residual | + 5. |
| Region No. 5, N.W., mean residual | + 4. |
| Region No. 7, W., mean residual | − 3. |
| Region No. 8, E., mean residual | − 2. |
| Region No. 9, S., mean residual | + 1. |

It is seen that the residuals average several times as great in India as in the United States, which leads him to conclude that "Speaking generally it would appear that isostatic conditions are much more nearly realized in America than in India, i.e., if we are to take the smallness of the residuals as an indication of the completeness of isostatic compensation."[2] Colonel Burrard, utilizing the Hayfordian computations, points out the existence of zones

[1] *Professional Paper No. 13, Survey of India*, 1912.

[2] *Op. cit.*, p. 4.

in India where the deflections of the plumb-line are actually in opposition to the directions called for by isostasy.[1] The major elements of the relief, the Himalayas, the plateau of India, and the surrounding ocean basins are of course largely compensated, but these figures show that in detail the hypothesis of complete isostasy is very far from the truth. Crosthwait suggests that the explanation for the difference between the United States and India probably lies in the magnitude of the recent upheavals of the crust in that part of the globe. Nevertheless such upheavals cannot exceed the strength of the crust, and in India, therefore, perhaps may be better observed than in the United States the maximum strains which the earth is competent to endure.

It may be concluded, therefore, that the convergence of geodetic evidence shows the crust to be competent to sustain loads measured by the weight of several thousand feet of rock extending over circular areas some tens of thousands of square miles in area. This is a measure of crustal strength twenty, fifty, or even a hundred fold greater than that advanced in recent years by the leading champions of high isostasy.

## FURTHER GEODETIC WORK NEEDED FOR GEOLOGIC PROBLEMS

It has been the intention in the preceding analysis to show two things: first, that the data set forth by Hayford and Bowie are of great value to geology and establish new methods of research, but, second, that the difficulties inherent in the observations and their mathematical treatment, and the fewness of the stations in comparison with the heterogeneity of the earth, are such that the conclusions from the geologic study of deltas in the first part of this paper are as convincing and perhaps as accurate as the present results of the geodetic studies. The latter, however, opens for the whole earth a field of investigation which the geologic evidence covers very locally and imperfectly, a world-wide field which should be pursued for the geologic as much as for the geodetic bearings.

By means of the divining rods of pendulum and plumb-line the heterogeneities of mass and the loci of strain in the outer crust of

[1] "On the Origin of the Himalaya Mountains," *Professional Paper No. 12, Survey of India*, 1912.

the earth should be sought out and measured in detail. For this work it would seem that many new stations would have to be established; in groups so as to reduce the errors of each locality; in sets so as to attack particular phases of the problems. For example, it would appear that gravity stations should be located in pairs close together and of as great a difference in elevation as possible. Certain stations should be located within areas of plateaus spared by circumdenudation, such as the Cumberland and Allegheny plateaus; others should be located in the broad erosion basins. Deflection stations should be located on the lines separating regions of erosion from those of circumdenudation, and also on the lines separating areas of upwarp from those of downwarp. A network should inclose, finally, all centers of marked gravity anomaly or topographic deflection. Such an increase in the number of stations would permit the introduction of simple hypotheses of variable depth and rate and regional limits of compensation. But such an extensive program is within the reach only of some research institution. It needs the co-operation of geologists and geodesists. The location of stations with respect to surface features and their geologic history should be controlled by the geologist. The density of the rocks to the limits exposed by the structure should also be determined by him. The geodesist, on the other hand, should seek out the hidden heterogeneities in the crust and guide the details of the work.

[*To be continued*]

# DIASTROPHISM AND THE FORMATIVE PROCESSES. VII

## PERIODICITY OF PALEOZOIC OROGENIC MOVEMENTS

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### INTRODUCTION

Within the last few years there has been a growing belief among American geologists that diastrophism, in its greater manifestations, has been periodic, rather than continuous. According to this view the earth has passed through periods of diastrophic activity alternating with periods of relative quiescence.[1] During the more protracted of the periods of quiescence the earth's surface is believed to have remained stable sufficiently long to allow base-leveling to reach an advanced stage, and this is held to imply stability, for, without stability in the outer portion of the earth, mature base-leveling is scarcely possible. During such a time of base-leveling, stresses within the body of the earth must be accumulating steadily, but because of the high rigidity now apparently demonstrated these stresses show little outward manifestation of their presence for a long time, until finally, according to this view, the increasing internal stresses reach such an intensity that the mass of the earth can resist no longer but yields, and a period of active deformation succeeds the state of crustal inactivity. The deformation once inaugurated continues till the stresses are essentially eased. Then another period of quiescence sets in, to be followed in turn, after a long interval during which new stresses have developed, by another deformative outbreak.

Such diastrophic movements are held to be in themselves major events in the earth's history; and, in addition, they are the direct

[1] T. C. Chamberlin and R. D. Salisbury, *Geology*, III (1906), 192, 193; T. C. Chamberlin, "Diastrophism as the Ultimate Basis of Correlation," *Jour. Geol.*, XVII (1909), 685–93; Charles Schuchert, "Paleogeography of North America," *Bull. Geol. Soc. Am.* XX (1910), 427–606; Bailey Willis, "Principles of Paleogeography," *Science*, XXI, No. 790 (1910), 246–49; E. O. Ulrich, "Revision of the Paleozoic System," *Bull. Geol. Soc. Am.*, XXII (1911), 281–680.

cause of extensive changes in sedimentation; and these, together with climatic and other effects that follow, influence profoundly the life-development. Thus, back of both stratigraphy and paleontology lies diastrophism, which furnishes the conditions upon which they depend.[1] If periods of diastrophism are thus truly the ultimate basis of correlation, they form a subject of inquiry of prime importance.

The chief purpose of the study upon which this paper is based is to determine to what extent past diastrophic movements of the higher order actually have taken place—simultaneously in different parts of the globe and periodically in the same region—with a view to the bearing of the facts on the determination of systems and periods, and on the broader correlations of geologic events. It is an attempt to test the hypothesis that the geologic periods represent, in the main, periods of relative quiescence, during which there were sea-transgressions and widespread sedimentation, and that they were separated one from another by diastrophic disturbances of shorter duration. The study is an attempt to discover whether the principal manifestations of diastrophic activity in one portion of the globe can be correlated approximately with corresponding disturbances in other parts of the globe, and whether the synchronous disturbances have been sufficiently widespread and effective in their manifestations to constitute a satisfactory basis for dividing geologic time into periods.

There can be little doubt that there are various grades of deformation and that most or all of these are serviceable as markers of time divisions of some order, but in the present discussion I shall try to limit the deformations recognized to those that involve some notable folding, or at least to unconformities so marked as to imply notable warping somewhere. This paper will be further limited in that it offers merely a preliminary selection of data relative to earth movements of the Paleozoic era that have been gathered from various accessible sources but not yet fully traced to their original sources and critically examined. The data are a part of a more general collection which includes the Mesozoic and Cenozoic eras. The present paper is but a modification of one read at the Twelfth

[1] T. C. Chamberlin, "Diastrophism as the Ultimate Basis of Correlation," *Jour. Geol.*, XVII (1909), 692.

International Geological Congress at Toronto in August, 1913, and is presented here because it was undertaken as a part of the series of studies now appearing under the title "Diastrophism and the Formative Processes."

For brevity in designating the various diastrophic disturbances, my father has found it convenient in his lectures to use such terms as the following: Ordovicides for foldings or strong diastrophic movements which took place either at or near the close of the Ordovician period; Silurides for like movements at or near the close of the Silurian period; and similarly, Devonides, Carbonides, and Permides for movements connected with the closing stages of the Devonian, Carboniferous, and Permian periods. For movements near the close of the Mississippian, or Lower Carboniferous period, the term Culmides is used in place of a more cumbersome derivative from the name Mississippian. These terms will be used in this paper.

### CAMBRIDES?

The Proterozoic era seems to have closed with profound diastrophic movements in most parts of the world where satisfactory identifications have been made. At the close of the era the sea was quite generally withdrawn into the deep basins. The Paleozoic era which followed commenced with advancing seas in which the Cambrian sediments were laid down unconformably, for the most part, upon eroded and trunkated Proterozoic strata. During the Cambrian period there appears to have been a general, but more or less fluctuating, advance of the sea up to the close of what is usually classed as Upper Cambrian. Following this, in the debatable ground that lies between the well-recognized Upper Cambrian and the undoubted Ordovician, evidence of some diastrophic movements appears, but, so far as present data go, these movements do not seem to be of the decided class to which this paper chiefly relates. Rather widespread unconformities occur near this horizon in various parts of the Mississippi and St. Lawrence basins, but they are not of such a nature as seriously to affect the general parallelism of the Cambrian and Ordovician systems.[1] There are discordances be-

[1] Chamberlin and Salisbury, *Geology*, II (1906), 311–12; Ulrich, "Revision of the Paleozoic System," *Bull. Geol. Soc. Am.*, XXII (1911), 614–16, 626–28; Schuchert, "Paleogeography of North America," *ibid.*, XX (1910), 522–29.

tween the Cambrian and Ordovician in Bohemia, in certain parts of the Armorican massif,[1] in the north of Wales,[2] in Norway,[3] and at Spiti in the Himalayas,[4] but no clear evidence of important folding appears. It is not clear that any one of these unconformities is of the higher order; they seem rather to be intercurrent movements of the minor order in what was, in general, a time of crustal quiescence. In general much hesitation and indecision has been shown by geologists in determining where to draw the dividing line in the transition series between the Cambrian and the Ordovician. In this study it is the periods of pronounced crustal crumpling, or of marked differential movement, that are especially sought as unequivocal representatives of events of the first order of importance; for unconformities of the simpler order are liable to represent events of a minor order of importance. Judged by this rather severe standard, the transition from the Cambrian to the Ordovician was relatively quiet; it does not now appear that there were pronounced crustal movements, and hence, on the basis chosen, it does not seem clear that the two were sharply separated periods in the earth's history. Throughout most of the globe where evidence is available, there was no radical change in the areas or the attitudes of sedimentation. This indecisiveness in the character of the diastrophic movements associated with the close of the Cambrian and the opening of the Ordovician leaves the question of the separateness of the two as distinct periods a somewhat open one considered from the diastrophic basis simply.

### ORDOVICIDES

The greater part of the Ordovician period seems to have been a time of crustal quiescence, in the sense of the term used in this discussion, but its closing stages were marked by pronounced disturbances in various portions of the globe. These are the first crustal deformations of the higher order for which I have found clear evidence since the close of the Proterozoic.

[1] Emile Haug, *Traité de géologie*, II (1911), 634–35.

[2] A. J. Jukes-Browne, *The Building of the British Isles* (1911), p. 78.

[3] Eduard Suess, *The Face of the Earth*, Sollas trans., II (1906), 52.

[4] A. de Lapparent, *Traité de géologie*, 5th ed., II (1906), 808.

In North America the disturbances occurred principally on the eastern side. A portion of the Atlantic border was strongly folded. According to Campbell, the general region lying eastward from what is now the Appalachian Valley, throughout much of its extent, was subject to disturbing influences at several periods during the Paleozoic.[1] This is in accord with the view that the source of the vast quantity of clastic sediment which was laid down in the Appalachian geosyncline in the course of the Paleozoic was the old land of Appalachia lying between the present mountains and the edge of the continental shelf. So great a volume of the sediments derived from this not very extensive land area is thought to imply a repeated renewal of the land by uplift.

Definite evidence of one such disturbance is found in the Taconic Mountains of western New England and the adjacent portions of New York and Canada. In this region the Cambrian and Ordovician strata are sharply folded and faulted while the Silurian strata rest unconformably upon the flanks of these folds and are not incorporated in them.[2] Today only the obscure stumps of these ancient mountains are visible, but they seem once to have constituted a great range. Thrust faulting, not unlike that of the southern Appalachians, was prominent but perhaps on a somewhat smaller scale.[3]

This ancient chain of mountains extended far to the northeast, paralleling the present coast. A large tract in northeastern Maine, northwestern New Brunswick, and the Gaspé Peninsula is occupied by a broad synclinorium of Silurian strata which appear to lie unconformably upon folded and eroded Cambrian rocks.[4] From Maine the eastern margin of the Silurian extends northeastward across New Brunswick to the Bay of Chaleur. In surveying the line between the Cambro-Ordovician and the Silurian, Bailey found

[1] M. R. Campbell, "Paleozoic Overlaps in Montgomery and Pulaski Counties, Virginia," *Bull. Geol. Soc. Am.*, V (1894), 178–79.

[2] James D. Dana, *Manual of Geology*, 4th ed. (1895), p. 386.

[3] C. D. Walcott, "The Taconic System of Emmons," *Am. Jour. Sci.*, 3d Ser., XXXV (1888), 315–20; James D. Dana, *op. cit.*, p. 528.

[4] L. W. Bailey and William McInnes, "Explorations in New Brunswick, Quebec and Maine," *Ann. Rept. Geol. Surv. Canada*, New Ser., III (1889), 29–31 M.

"incontestable evidence of discordance along its whole length."[1] The fossiliferous Silurian slates are marked by a heavy basal conglomerate whose pebbles have been derived from the Cambro-Ordovician strata, but it is not clear how much time is represented by the unconformity.

The width of the belt affected by the movement may have been considerable. In southern Quebec, southeast of the St. Lawrence River, isolated areas of Silurian strata, largely limestones, occur in some of the synclines, and these Silurian beds are found to lie unconformably upon Ordovician strata, indicating that this region also was affected by the movement.[2] But the effects of the uplift were not felt upon the north side of the Gulf of St. Lawrence, for on Anticosti Island the accumulation of the great limestone formation which commenced in Ordovician times continued without a break into the Silurian.[3]

From the region of the Taconic Mountains of New England and New York evidences of this uplift may be traced southwestward. What appear to be evidences of the same disturbance have been noted on the east side of the Appalachian Mountains as far south as Virginia.[4] In 1892, N. H. Darton found some crinoids, which Walcott has assigned to the Upper Ordovician, in the slate quarries at Arvon, in the Piedmont region of Virginia.[5] While the age of the deformation and metamorphism of these rocks is not established, Dana nevertheless regarded this strip as possibly a part of a long Westchester Taconic range which passed just west of Philadelphia and Baltimore.[6] Very possibly also a portion of the folding of early Paleozoics in New Jersey may belong to the Taconic movement. But here again the age of the folding has not been definitely placed.

[1] L. W. Bailey, in G. M. Dawson's *Summary Rept., Geol. Survey of Canada*, XIII (1900), 146–48 A.

[2] R. W. Ells, cited by Willis, "Index to the Stratigraphy of North America," *Prof. Paper 71, U.S. Geol. Survey* (1912), p. 250.

[3] W. B. Scott, *An Introduction to Geology* (1907), p. 567.

[4] M. R. Campbell, "Paleozoic Overlaps in Montgomery and Pulaski Counties, Virginia," *Bull. Geol. Soc. Am.*, V (1894), 189.

[5] N. H. Darton, "Fossils in the 'Archean' Rocks of Central Piedmont Virginia," *Am. Jour. Sci.*, 3d Ser., XLIV (1892), 50–52.

[6] J. D. Dana, *op. cit.*, p. 532.

In the northwestern portion of the state, where the Silurian strata are present to aid in correlation, this critical time period is represented by an extensive unconformity, but there has been no folding there. But that is distinctly west of the Taconic belt.[1] Kümmel discusses the matter thus:

> Contrary to long-prevalent and apparently well-established belief, the lower and middle portions of the Silurian system are not represented in New Jersey. Their absence in this and adjoining regions is indicative of somewhat widespread earth movements, unaccompanied in this region by folding, which closed the period of deposition indicated by the Martinsburg sediments, or possibly overlying beds afterward removed by erosion, and raised the region above the zone of sedimentation. When deposition began again, late in Silurian time, beds of coarse conglomerate were laid down. . . . .

This is the Shawangunk formation between which and the Martinsburg shale there is a gap representing the upper part of the Ordovician and all of the Silurian below the Salina of the full New York section, but there is no marked divergence of dip and strike where the two formations outcrop in proximity.[2]

In general, throughout most of the Appalachian province the youngest Ordovician (Richmond) beds are lacking, and an angular discordance between the Ordovician and Silurian at many points implies an emergence corresponding to the Taconic folding to the northeast. Ulrich states that at this time the whole Appalachian region was considerably elevated and the middle and eastern parts of Appalachia itself most probably subjected to profound orogenic movements.[3] Dana in particular has urged the magnitude and importance of this early mountain development. Because evidences of this movement, which was so intense in New England and New York, have been recognized over a much wider area, he regarded the Taconic Range of western New York as only one in a great Taconic system of mountains.[4] This great system lay entirely

[1] Stuart Weller, "The Paleozoic Faunas of New Jersey," *Geol. Survey of New Jersey, Rept. on Paleontology*, III (1902), 54.

[2] H. B. Kümmel, "Geological Section of New Jersey," *Jour. Geol.*, XVII (1909), 356–57.

[3] E. O. Ulrich, "Revision of the Paleozoic System," *Bull. Geol. Soc. Am.*, XXII (1911), 436–37.

[4] James D. Dana, *Manual of Geology*, 4th ed. (1895), pp. 531–32.

to the east of the present Appalachians, more or less paralleling that later system as it does the coast. This Ordovician system may be regarded as a forerunner of the late Paleozoic Appalachians.

The local stratigraphic details in various portions of this general region, and the great extent of the emergence at this time are clearly pictured in the time scale for eastern North America given by Ulrich and Schuchert in their paper on Paleozoic seas and barriers in eastern North America.[1] It is the view of these authors that the disturbance was felt first in the southern portion of the Appalachian region and progressed thence northeastward along the axis of folding and westward toward the Mississippi basin, and so they believe it was not quite synchronous throughout the entire region affected. In the Lenoir basin (comprising the Athens and Knoxville troughs) the emergence followed the deposition of the Sevier shale, while in the Mississippi basin they regard the main emergence as having followed the Richmond, the time of the maximum uplift. The movement appears to have commenced with several minor pulsations in the closing stages of the Ordovician (Lorraine and Richmond) which quickly led to the great Taconic revolution which terminated the Ordovician, and which was one of the greatest movements in North American Paleozoic history. According to Ulrich and Schuchert, this revolution affected all North America, there being perhaps land throughout from Richmond to Oneida time. But the length of this land interval they believe cannot be satisfactorily ascertained as there are no Mississippi basin sea deposits by which its duration may be measured.

It appears quite widely in the literature that the Cincinnati Arch and Nashville Dome, in Ohio, Indiana, Kentucky, and Tennessee, originated also at this time. The basis for this view has been the widespread unconformity at the base of the Silurian. The Clinton follows the Ordovician and contains in its basal member rounded fragments of the Ordovician rocks[2] which suggests that the primary uplift of these domes may have been a feature of the Ordovicide movement. Foerste, however, regards the evidence for

[1] E. O. Ulrich and Charles Schuchert, "Paleozoic Seas and Barriers in Eastern North America," *Bull. LII, New York State Museum* (1901), p. 658.

[2] Bailey Willis, *op. cit.*, p. 232.

the origin of the Cincinnati geanticline at this time as inconclusive, and, instead, places its inception between the Niagaran and the Middle Devonian, while it is recognized that the geanticline owes its present proportions to later upwarping which occurred probably in post-Mississippian times.[1] Minor oscillations and tilting, according to Ulrich, occurred in the region of the Cincinnati and Nashville domes much earlier (during the Ordovician period) but these movements were not of the more pronounced type.[2]

In North America the principal orogenic disturbances of the early Paleozoic thus occurred near the close of the Ordovician and were located near the Atlantic border where thick sediments had been accumulating. Europe seems to have behaved similarly. Throughout much of continental Europe the relatively quiescent conditions of the Ordovician continued with little interruption into the Silurian. But in the British Isles, where the Cambro-Ordovician strata are very thick, there were pronounced orogenic movements which were approximately contemporaneous with the Taconic revolution of North America. Over large areas the Lower Silurian rocks were upheaved, more or less contorted, and in many places suffered a great amount of denudation before the deposition of the Upper Silurian strata began.[3] A large portion of the British Isles became land, and Jukes-Browne believes that this continental land included also a large part of the North Sea and nearly the whole of Norway.[4] The results of this disturbance are conspicuous in the original tract of Siluria (western England and the adjacent portion of Wales) where a decided unconformity separates the Ordovician from the Silurian. In some places the latter extends across the trunkated edges of the former, group after group, till they rest directly upon the Cambrian beds. Ramsay's diagram of the section between Church Stretton and Chirbury in Shropshire shows nearly horizontal Llandovery (basal Upper Silurian) beds cutting across nearly

[1] A. F. Foerste, "The Ordovician-Silurian Contact in the Ripley Island Area of Southern Indiana, with Notes on the Age of the Cincinnati Geanticline," *Am. Jour. Sci.*, 4th Ser., XVIII (1904), 321–42.

[2] E. O. Ulrich, *Bull. Geol. Soc. Am.*, XXII (1911), 416–19.

[3] A. C. Ramsay, *The Physical Geology and Geography of Great Britain*, 6th ed (1894), p. 74.

[4] A. J. Jukes-Browne, *The Building of the British Isles* (1911), pp. 94, 97.

vertical Cambrian and Ordovician strata.[1] It is evident, therefore, that in this region considerable disturbance and extensive denudation followed the Ordovician and preceded the commencement of the Silurian sedimentation.[2]

Of the events in Asia at this time much less is known. But it is known that in the eastern portion of that continent the Ordovician seas withdrew late in the period, leaving large areas emerged in Mongolia and Manchuria[3] and probably also in northern China where the Ordovician is terminated by unfossiliferous dolomites which were probably lagoon deposits. The Silurian has not yet been recognized above them and very likely was never laid down there.[4] But we have as yet no good evidence of any pronounced mountain-making movements in Asia at this time.

In the Andine region of South America there is a suggestion of diastrophic movements following the Ordovician, for the Silurian is often lacking there, the Devonian resting directly upon the Ordovician.[5]

The eastern portion of the Australian continent was the locus of mountain-making movements at several periods during the Paleozoic. In New South Wales, the close of the Ordovician was attended by both volcanic and diastrophic disturbances. Süssmilch states that at Tallong, the one place where a junction between the Ordovician sediments and those of the next period has been observed, a well-marked unconformity occurs. The evidences of this region are interpreted by Süssmilch as showing that at the close of the Ordovician period there occurred extensive earth movements by which the marine sediments and volcanic ash, which had accumulated to a thickness of many thousands of feet, were pressed into a series of folds trending approximately north and south, and that these suffered denudation so that when the sea readvanced upon these land areas in Silurian time, the new sediments were deposited unconformably upon the trunkated edges of the Ordovician strata.[6]

[1] A. C. Ramsay, *op. cit.*, p. 77.

[2] Sir Archibald Geikie, *Textbook of Geology*, 4th ed., II (1903), 953.

[3] A. de Lapparent, *Traité de géologie*, 5th ed., II (1906), 807.

[4] Emile Haug, *Traité de géologie*, II (1911), 653.

[5] *Ibid.*, p. 657.

[6] C. A. Süssmilch, *Geology of New South Wales* (1911), p. 18.

These evidences of pronounced folding movements in different quarters of the globe at the close of the Ordovician are supported by the extensive withdrawals of the sea from the line of maximum transgression in the mid-Ordovician, to the shore lines implied by the early Silurian beds in many other regions which were not affected by the more violent disturbances. This was a time of general disturbance; but it remains for future study to establish just how nearly synchronous these widespread disturbances were.

### SILURIDES

During the greater part of the Silurian period there was a relative freedom from diastrophic disturbances of the major sort. But toward the close marked disturbances set in and may be said to have terminated the epicontinental phase of the Silurian sedimentation in various parts of the globe. North America was affected chiefly by movements of the milder sort but certain portions of Europe suffered from intense orogenic deformation. In North America a comparatively rapid emergence of the continent began with the Guelph and continued until the Silurian period closed with the land nearly as extensive as it was at the beginning of the period, when most of the North American continent stood above water.[1] While the very widespread unconformities indicate a general epeirogenic movement at this time, or else a withdrawal of the sea, or both, very little evidence of pronounced folding has as yet been found on the mainland of this continent. Some slight folding, however, has been recognized on the Atlantic border. Campbell, in a summary of the periods of Appalachian folding in Virginia, has described a deformative movement which, preceding the deposition of the Walker black shale, has folded the limestones and marks the division line between the Silurian and Devonian. It is the principal period of deformation in the region before the great Appalachian revolution which came at the close of the Paleozoic.[2]

Siluride movements following the extensive Silurian sedimentation were especially prominent in the higher northern latitudes.

[1] Charles Schuchert, "Paleogeography of North America," *Bull. Geol. Soc. Am.*, XX (1910), 491, 540.

[2] M. R. Campbell, *Bull. Geol. Soc. Am.*, V (1894), 189–90.

In the Yukon region of Alaska, according to Brooks and Kindle, it seems probable that one of the recurrent epochs of crustal disturbances took place in early Devonian or late Silurian times, for all the rocks laid down before this period appear to fall into the metamorphic class, though they have suffered a varying amount of alteration. Granitic intrusions are associated with this folding and it is probable that this epoch was closed by an uplift followed by erosion.[1]

In northeast Greenland, what appears to be an orogenic movement at the close of the Silurian has been recognized and described by Nathorst as follows:

> The Silurian strata, as we have seen, are folded and compressed and partly metamorphosed. If this bears any relation to the formation of a mountain range, the folding took place before the deposition of the Devonian strata, for the latter show only a relatively slight amount of disturbance. Otherwise it must be surmised that the folding was the result of a depression of the Silurian strata along a fault at their eastern border, or perhaps between such a fault and another which can be imagined as passing west of the present boundary of the Archean.[2]

This folding in northeast Greenland parallels and may perhaps be related to the great Caledonian folding of Scotland and Scandinavia.

In Europe the close of the Silurian was a time of much greater disturbance. Flexing and faulting of the crust at this time developed a chain of stupendous mountains in northwestern Europe. The present stumps of these great mountains run throughout the length of Scandinavia; reappear in the northwest highlands of Scotland, and extend onward into Ireland, Wales, and England. Evidences of these ancient mountains are to be recognized as far south as Devonshire. To this chain Suess has applied the name Caledonian, recognizing it as one of the greatest ranges of the past.[3] Both in Scandinavia[4] and in the Scottish Highlands[5] the formation

[1] A. H. Brooks and E. M. Kindle, "Paleozoic and Associated Rocks of the Upper Yukon, Alaska," *Bull Geol. Soc. Am.*, XIX (1908), 312–13.

[2] A. G. Nathorst, cited by Willis, *op. cit.*, p. 341.

[3] Eduard Suess, *The Face of the Earth*, Sollas trans., II (1906), 82–86; III (1908), 386–99.

[4] A. E. Törnebohm, "Grunddragen af det Centrala Skandinaviens Bergbyggnad," *K. Svenska Vetensk Akad. Handl.*, XXVIII (1896), 212.

[5] B. N. Peach, J. Horne, and others, "The Geological Structure of the Northwest Highlands of Scotland," *Mem. Geol. Survey of Great Britain* (1907), 463–594.

of this range was characterized, not only by sharp folding, but by some of the most remarkable overthrust faulting of which we have any record. The horizontal thrusting amounts to many miles.

According to Lake and Rastall this folding occurred during the Devonian,[1] since it followed the deposition of a portion of the Old Red Sandstone. In Wales this portion passes downward conformably into the Silurian. Sir Archibald Geikie likewise stated that the Old Red Sandstone of Britain consists of two divisions, the lower of which passes down conformably into the Upper Silurian deposits, while the two divisions are separated one from another by an unconformity which makes a great physical and paleontological break.[2] This break presumably corresponds to the mountain-building.

But Jukes-Browne, writing in 1911, states that some beds which were formerly called Old Red Sandstone are now placed in the Silurian, while the mass which was formerly called "Middle Old Red Sandstone" is now admitted to be the true Lower Old Red, and known from its fish fauna to belong to the Lower Devonian.[3] The movement in Wales he places at the beginning of the Devonian,[4] while the principal physical features of Scotland had been developed between the close of the Ordovician and the opening of the Devonian period. In the southern uplands, where the time limits are more closely drawn, the plication follows the Silurian, for that system is included in the crumpling. The time of deformation is finally summed up by Jukes-Browne: "Thus the first uplift of the outer ranges may have taken place in Silurian time; the date of the central axis we know [apparently close of Silurian] and the final intense development of the pressures in the outer ranges may have occurred either at the same time or even during the actual formation of the lowest Old Red Sandstone."[5]

The Scandinavian portion of this great mountain system apparently affords less definite evidence of the precise time of this disturbance, but Haug concludes that although we cannot, in the

[1] Philip Lake and R. H. Rastall, *Textbook of Geology* (1910), pp. 342–43.

[2] Sir Archibald Geikie, *Textbook of Geology*, 4th ed., II (1903), 1006–7.

[3] A. J. Jukes-Browne, *The Building of the British Isles* (1911), p. 114.

[4] *Ibid.*, p. 119.

[5] *Op. cit.*, p. 126.

absence of incontestable Devonian deposits, determine in a precise manner the age of the folding in Scandinavia, we can place it, from the analogy with Scotland, at the junction of the Silurian and Devonian.[1]

Holtedahl has noted a northward continuation of the Caledonian mountain-folding in Spitzbergen, but as he found beds which he believes to belong to the uppermost Silurian resting unconformably upon the Silurian strata which are incorporated in the folds, he would place the date of the folding late in the Silurian instead of at its close, which, if correct, would seem to indicate that the disturbance commenced in the northern portion of the Caledonian chain somewhat earlier than it did farther south.[2]

While there was intense crumpling in the Grampian geosyncline and in Scandinavia along this northeast-southwest Caledonian axis at the beginning of the Devonian, folding also took place, in central Europe, at approximately the same time, along a northwest-southeast axis. The folded belt extends from the Ardennes of France through the Taunus and Thüringerwald into Moravia, where this system of folds disappears under the great overthrusts of the Carpathians, which are of much more recent origin.[3] Farther west than the Ardennes, in the Cotentin region of northwestern France, Lecornu has described Siluride folding which may be a westward continuation of this mountain system of central Europe.[4]

In the Sahara Desert recent explorations by Gautier have shown the existence of folding during the Caledonian epoch. The early Devonian strata in the Oran Sahara rest in horizontal or slightly undulating beds upon folded Silurian strata.[5]

According to Hauthal, South America also suffered from deformative movements at this time. In the Sierra de la Ventana, of Argentina, Hauthal found that the older Paleozoic sedimentaries

[1] Emile Haug, *Traité de géologie*, II (1911), 730.

[2] Olaf Holtedahl, personal communication.

[3] Emile Haug, *op. cit.*, p. 732.

[4] L. Lecornu, cited by Suess, *op. cit.*, IV, 48.

[5] R. Chudeau and E. F. Gautier, "Sur le structure géologique du Sahara central," *Comptes rendus*, CLXI (1905), 374–76.

were affected by folding which took place between the Silurian and Devonian.[1]

Over considerable areas in southeastern Brazil horizontal beds of Devonian age rest unconformably upon folded and metamorphic rocks for the most part of probable pre-Cambrian age, but possibly including some strata representing the Cambrian or Lower Silurian.[2] This is the most conspicuous period of deformation to which the eastern half of the continent of South America has been subjected since Archean times. It resulted in a great chain of mountains, of which the present Serra do Espinhaço, or Backbone Range of Brazil, represents the roots. The time of the crumpling and faulting has not yet been closely determined, and this cannot yet be classed as a Siluride movement, though Hauthal believes that the Sierra de la Ventana, in which he found evidence of a Siluride movement, are related in origin to the Brazilian Highlands.

In New South Wales, according to Süssmilch, the Silurian period was brought to a close after a long period of sedimentation, by a pronounced deformative movement which folded and elevated the Silurian strata to such an extent that much of the country was raised above sea-level. Incomplete knowledge of the nature and distribution of the succeeding Devonian sediments makes it impossible to form any definite opinion as to the extent of this movement.[3] But farther north, in the Narrigundah Gold Field of Queensland, Devonian strata are again found resting horizontally upon folded Silurian beds.[4]

Like the closing stage of the Ordovician, the end of the Silurian period was a time of rather general crustal disturbance which reached extreme intensity in certain regions. Present knowledge is not adequate, and correlations are not sufficiently exact, to determine how nearly simultaneously the disturbances appeared in the

[1] R. Hauthal, "Excursion à la Sierra de la Ventana," *Publicaciones de la Universidad de La Plata*, 1901, pp. 30.

[2] Hartt, cited by Suess, *op. cit.*, I, 508. J. C. Branner, *Geologia Elementar, Rio de Janeiro* (1906), p. 217.

[3] C. A. Süssmilch, *An Introduction to the Geology of New South Wales* (1911), p. 33.

[4] H. I. Jensen, "The Building of Eastern Australia," *Roy. Soc. Queensland*, XXIII (1911), 165.

different regions; and that is a crucial point. But from available data it would seem that the deformation was in progress at some points as early as the latter part of what has been classed as Silurian, while it persisted at other points into what has been classed as early Devonian. Even if the identifications are strictly decisive, such a range of time for a major deformative movement would not seem more than is to be expected under the hypothesis of a genetic relationship between the movements in widely separated quarters of the globe, for absolute simultaneity is improbable. The critical question, however, lies between the weight that is to be given to the identifications of the dividing line that has been fixed by geologists in their local studies in the cases cited, and that which may properly be given to the diastrophic movements when they shall have received the critical attention that has been given to the stratigraphic and paleontologic criteria. If a real discrepancy is found ultimately, which class of evidence shall give way to the other?

### DEVONIDES

In North America the most noteworthy orogenic disturbances connected with the Devonian period occurred near its close in eastern Quebec, New Brunswick, Maine, and perhaps also southwestward through the tract of Appalachia which was rather disposed toward upward movements during the Paleozoic. In the Gaspé Peninsula of Quebec the Bonaventure conglomerate of late Devonian, or early Mississippian, age was laid down unconformably upon the vertical edges of the Silurian and Devonian strata about Percé.[1] The Devonian and older strata have been thrown into pronounced folds of the Appalachian or Jura type, indicating that a conspicuous mountain range was developed here after the deposition of these Devonian strata. The youngest formation included in the folded mountains is the Gaspé sandstone, which has been correlated by Clarke with the Hamilton of New York.[2] The great folds of Gaspé therefore arose some time between the late Hamilton and the beginning of the Mississippian, with the evidence tending

[1] J. M. Clarke, "Early Devonic History of New York and Eastern North America," *Mem. New York Mus.*, No. 9 (1908), 92–102.

[2] J. M. Clarke, *op. cit.*, pp. 86–88.

to show that the disturbance came within the later Devonian rather than at its close.[1]

These movements apparently also affected a portion of Nova Scotia, for in the MacArras Brook region, according to Ami, the Lower Carboniferous strata rest unconformably upon the upturned edges of the Lower Devonian of that region.[2] Though the folding is here less definitely located than in Gaspé, both foldings would seem to be manifestations of the same diastrophic disturbance.

Evidences of the same uplift and folding are to be looked for in Appalachia. Following the black Hamilton shales from New York to southern Virginia there occurs a great volume of sandy shale and argillaceous sandstone comprising the Jennings and Hampshire formations of Maryland, or the Chemung and Catskill of New York. Willis has estimated that if this mass of sediment could be restored upon a sea-level plain corresponding in shape and size to Appalachia, it would produce a mountain range closely resembling in height, extent, and mass the Sierra Nevada of California.[3] These he calls the Devonian Highlands. Their elevation would follow the Hamilton and thus correspond closely in time with the folding period in Gaspé.

At the close of the Devonian much of the continent of South America stood out of water.[4] In northeastern Argentina, to the west of the Cerro del Agua Negra, Bodenbender found the thick Devonian formations unconformably overlain by red Permo-Carboniferous sandstones.[5] The time of this movement has not been as yet closely determined.

But the greatest Devonide movements which have yet been recognized are those of Australia. The close of the Devonian was one of the greatest mountain-making epochs of New South Wales, according to Süssmilch—of such importance, indeed, that the name

[1] *Ibid.*, pp. 14–15.

[2] H. M. Ami, "Meso-Carboniferous Age of the Union and Riversdale Formations, Nova Scotia," *Bull. Geol. Soc. Am.*, XIII (1902), 533.

[3] Bailey Willis, "Paleozoic Appalachia or the History of Maryland during Paleozoic Time," *Maryland Geol. Survey*, IV (1902), 61–62.

[4] Charles Schuchert, *Jour. Geol.*, XIV (1906), 738.

[5] G. W. Bodenbender, *Boletin de la Academia Nacional de Ciencias de Cordova*, XV (1897), 201.

Kanimbla epoch has been suggested for this mountain-making period.[1] Süssmilch states that the folding must have taken place either at the close of the Devonian, for the Devonian beds are infolded, or, at the latest, early in the Caboniferous, for the Devonian strata had been greatly eroded before the horizontal Permo-Carboniferous strata were laid down. The general movements were on such an extensive scale as to convert the greater part of New South Wales into land. The folding was accompanied by batholithic intrusions.

In northwestern Europe, where accumulated strains had been relieved by such an extensive and remarkably vigorous crustal deformation at the close of the Silurian, the Devonian and early Carboniferous periods were a time of comparative quiescence. Devonide movements, however, have been recognized along a belt which, beginning in Brittany, includes the Armorican massif, the basin of Saarbrück, the Vosges, Black Forest, Thüringerwald, and continues into lower Silesia. These movements occurred either at the dividing line between the Devonian and the Lower Carboniferous, or very early in the latter period.[2]

Suess also implies that this chain may be related to one in the southern Tian Shan Range in central Asia, where an unconformity with folding at the base of the Lower Carboniferous represents an east-and-west line of Devonide wrinkling.[3] A possible connecting link between these widely separated wrinklings is suggested by Boutscheff's observations in the Balkans, northeast of Sophia, where steeply overfolded Upper Silurian graptolite beds are covered unconformably by the Culm.[4] But the age of this folding is not closely limited.

### CULMIDES

The Lower Carboniferous or Mississippian period seems to have been one of comparative quiescence, as implied by the extensive formation of limestone which characterizes this portion of the

[1] C. A. Süssmilch, *An Introduction to the Geology of New South Wales* (1911), pp. 51–52.

[2] Emile Haug, *op. cit.*, p. 831.

[3] Eduard Suess, *The Face of the Earth*, Sollas trans., IV (1909), 2.

[4] S. Boutscheff, cited by Suess, *op. cit.*, p. 16.

earth's history in so many parts of the globe. But at the close of the period there was a widespread withdrawal of the sea. In North America the seas retired from a large part of the United States, New Brunswick, and Nova Scotia, to such an extent that when the sea again advanced in the Pennsylvanian or Upper Carboniferous period, the new sediments were laid down unconformably upon the eroded Mississippian beds over wide areas. This unconformity at the top of the Mississippian, or at the base of the Millstone Grit, is continued very widely throughout most of the interior and western states and an unconformity at about this same horizon appears also at various points in Alaska.[1] It was chiefly because of the unconformity which occurs at this horizon over such wide areas, not only in North America, but in other continents as well, that the portion of the Carboniferous below the unconformity was urged as a separate period under the name Mississippian.

Distinct folding movements occurred in the Arbuckle region of Oklahoma. Near the close of the Mississippian or beginning of the Pennsylvanian, the rocks of the Arbuckle region were folded and the western part thrown into mountains. Faulting also occurred on a large scale.[2] As a result of the elevation of these mountains at this time, with the attendant acceleration of erosion and rapid clastic sedimentation, the sediments of the succeeding Pennsylvanian period have reached a thickness in the adjacent portion of Arkansas of 18,000 feet.[3] These Arkansas Coal Measures correspond to only a lower part of the Pennsylvanian.[4]

In Europe conditions were somewhat similar. De Lapparent states that there was considerable volcanic activity from the Armorican region to the Vosges together with a complete withdrawal of the sea from the region, at the close of the Dinantian, or Lower Carboniferous. At this time there was energetic folding in the Vosges on the eastern frontier of France, while evidences of

[1] A. H. Brooks and E. M. Kindle, "The Paleozoic Section of the Upper Yukon, Alaska," *Science*, XXV (1907), 182.

[2] J. A. Taff, "Geology of the Arbuckle and Wichita Mountains in Indian Territory and Oklahoma," *Prof. Paper 31, U.S. Geol. Survey* (1904), p. 37.

[3] T. C. Chamberlin and R. D. Salisbury, *Geology*, II (1906), 562.

[4] A. J. Collier, "The Arkansas Coal Field," *Bull. 326, U.S. Geol. Survey* (1907), p. 24.

similar orogenic disturbances are seen in the Laval coal basin on the borders of Brittany[1] and also in the Sudetes.[2] The Culm occupies a large area in southern Portugal. But the Upper Carboniferous of that country is very restricted in area and rests unconformably upon the rocks below, probably indicating a Culmide movement.[3]

Asia also shows evidences of mild disturbances, at least, following the Culm. In Hseng King, the southern province of Manchuria, Inouye states that the Upper Carboniferous is unconformable upon the Lower.[4] In the southern portion of the Tian Shan range in central Asia the Lower Carboniferous, according to Suess, is marked by unconformities with orogenic movements both above and below it.[5] The Lower Carboniferous shows folding which took place before the basal beds of the Carboniferous were laid down. The inference naturally drawn from Suess is that this folding occurred before the beginning of the Pennsylvanian, but from Keidel's original description the first beds to be deposited upon the trunkated folds are to be correlated with the uppermost Carboniferous of Europe.[6] Hence the folding may have taken place either at the close of the Culm or before the Stephanian of the Pennsylvanian period. From the fact that strong folding was so general a phenomenon in many of the neighboring ranges of central Asia in the middle of the Carboniferous period, it is possible that this folding in the Tian Shan occurred also at that time, and so would be a Westphalo-Carbonide movement.

### WESTPHALO-CARBONIDES

The closing of the Paleozoic era was accompanied by much diastrophism. Though sometimes referred to as a more or less continuous period of disturbance from mid-Carboniferous times till the close of the Paleozoic, a closer analysis seems to show that

[1] A. de Lapparent, *Traité de géologie*, 5th ed., II, 906.

[2] Eduard Suess, *op. cit.*, II, 69.

[3] K. G. Jane, *Encyc. Brit.*, 11th ed., XXII (1911), 135.

[4] K. Inouye, cited by Suess, *The Face of the Earth*.

[5] Eduard Suess, *op. cit.*, IV (1909), 2.

[6] Hans Keidel, "Geologische Untersuchungen im südlichen Tian Schan nebst Beschreibung einer obercarbonischen Brachiopodenfauna aus dem Kukurtuk-Tal," *N. Jahrb. f. Min.*, XXII, Beilage Bd. (1906), pp. 266–384.

there were at least two distinct periods of deformation, separated by a period of comparative quiescence. The first stage of disturbance falls at the close of the Westphalian epoch, and hence may take the name of Westphalo-Carbonide movement. At this time extensive warpings and folding affected large portions of central and southern Europe and gave rise to a notable series of mountains which are grouped under the names Armorican and Variscan chains,[1] or collectively the Hercynian system,[2] and sometimes designated the Paleozoic Alps.[3]

The area of Armorican folds has a breadth reaching from Bristol, England, on the north, to La Vendée on the south, a distance of 330 miles across the strike.[4] This broad belt was crumpled into a succession of parallel folds trending east and west. They extend from the Atlantic shores of South Ireland, Cornwall, and Brittany eastward through the Ardennes, Vosges, Schwartzwald, Taunus, Harz, Thüringerwald, Frankenwald, Erzgebirge, and on into the Sudetes and Carpathians and are probably continuous, beneath younger formations, with the Carboniferous chains among the Balkans, and with the folds of the same age in Dobrudja, near the Black Sea,[5] a really great range of mountains of which we have today only the stumps remaining.

It is generally agreed that the chief episode in the formation of this great mountain system occurred between the deposition of the Westphalian and that of the Stephanian series. On the north side of the chain—in the south of England, in the Ardennes, in the Harz, and in Westphalia—the folding follows the Westphalian, but as the Stephanian is absent from this belt the date of the folding cannot be closely determined, though it is certainly before the Saxonian which inaugurates the Permian transgression.[6] But in the central plateau, the principal orogenic movements antedate the Stephanian which rests directly upon the Dinantian and older

[1] Eduard Suess, *The Face of the Earth*, Sollas trans., II (1906), 86–111.

[2] Marcel Bertrand, "La chaîne des Alpes, et la formation du continent Européen," *Bull. Soc. Géol. France*, 3d Ser., XV (1887), 435–40.

[3] Emanuel Kayser, *Geologische Formationskunde*, 2d ed. (1902), p. 174.

[4] A. J. Jukes-Browne, *op. cit.*, pp. 178–88.

[5] Emile Haug, *op. cit.*, p. 830.

[6] *Ibid.*, p. 831.

rocks which are generally metamorphosed. In the basin of Laval (Mayenne) the Stephanian Coal Measures with a conglomeratic base lie unconformably upon overfolded Westphalian beds.[1]

Contemporaneously there occurred several belts of disturbance in England somewhat apart from the main range. Here are included the Lancastrian flexures and the folding of the Pennine range, sometimes called the backbone of England. The folding is pre-Permian and appears to have come rather late in the Carboniferous period. From the immense amount of rock material which must have been removed from the broad arch of the Lake District before the Permian sandstones were laid upon it, Jukes-Browne suggests that this erosion possibly occupied the whole of Stephanian time, thus making this folding of the same date as the Armorican flexures.[2]

The Malvern and Abberley Hills are but the worn-down remnants of a mountain chain which was formed in the limited interval between the deposition of the Lower and Upper Coal Measures.[3] According to Groom, this folding and faulting was essentially contemporaneous with that of the Hercynian system. This would seem to be so if the Upper Coal Measures of Britain are equivalent to the Stephanian, as they are given by Geikie.[4] But according to Jukes-Browne, the Stephanian is absent from England and the Hercynian disturbance came after the English Upper Coal Measures.[5] If this be the correct correlation, the formation of the Malvern and Abberley Hills would seem to have been accomplished slightly earlier than that of the main Hercynian system.

On the border line between Italy and Austria the Carnic Alps result from east-and-west plications which are referred to Carboniferous times, but the precise stage remains doubtful. The principal Paleozoic movements in the exterior chains of the western Alps as well as in the eastern Alps are referred to this period with similar qualification.[6]

[1] A. J. Jukes-Browne, *op. cit.*, p. 188. [2] *Ibid.*, pp. 189–92.

[3] T. T. Groom, "On the Geological Structure of Portions of the Malvern and Abberley Hills," *Quart. Jour. Geol. Soc.*, LVI (1900), 176–95.

[4] Sir Archibald Geikie, *Textbook of Geology*, II (1903), 1051.

[5] A. J. Jukes-Browne, *op. cit.*, p. 171. [6] Emile Haug, *op. cit.*, pp. 830–31

Also in the Pyrenees there was a stage of folding at about this time. In the Asturias, and doubtless in the greater part of the Iberian Peninsula, folding movements followed the Westphalian, coming probably before the Stephanian, but in any case before the Permian. From Galicia in the extreme northwest corner of the peninsula and from the north of Portugal, a number of nearly parallel folded ranges, closely packed, run southeastward into the great Meseta and continue as far as the valley of the Guadalquivir in southern Spain.[1] This intensely folded mountain system includes much of the Carboniferous together with much granite which, for the most part, was intruded during the Carboniferous period. As in the Asturias, here also the upper beds of the Carboniferous rest unconformably on the folded region, and the general structure of these mountains thus dates, like that of the Armorican and Variscan systems, from late in the Carboniferous period.

South of the Mediterranean there are evidences of Hercynian movements as far as the African Caledonian fold zone.[2] In the Atlas Mountains of Morocco the age of the closing Paleozoic folding has not been fixed more closely than between the close of the Lower Carboniferous and the beginning of the Permian. But in eastern Morocco and in south Oranais, the Devonian, Dinantian, and Moscovian (Westphalian) are found in concordance just as in Spain, which has led Haug to conclude that they belong to the same geosynclinal and to the same zone of folding.

In South Africa the most definite bench mark for correlation is afforded by the base of the Karroo System—the Ecca series, and especially its basal formation, the Dwyka conglomerate. Its widespread occurrence, its distinctive petrographical characteristics, and the fact that, while conformable in the south of Cape Colony with the uppermost member of the Cape System, it shows a varying degree of unconformity elsewhere, make the Dwyka conglomerate an excellent datum level.[3] In the north of Cape Colony, according to Hatch and Corstorphine, in Natal, Zululand, Rhodesia,

[1] Eduard Suess, *The Face of the Earth*, Sollas trans., II (1906), 126.

[2] G. B. Flamand and E. F. Gautier, cited by Haug, *op. cit.*, p. 831.

[3] F. H. Hatch and G. S. Corstorphine, *The Geology of South Africa*, 2d ed. (1909), p. 335.

Orange River Colony, and in the Transvaal, the Dwyka conglomerate rests unconformably upon the older rocks, generally upon the strata of the Cape System.[1]

The age of the Cape System is still somewhat uncertain; the middle member (Bokkeveld series) is of Devonian age, but the age of the upper member (Witteberg series) is more in doubt, as these beds have as yet yielded no remains of animals, and only rather poor specimens of plants. While little value can be placed upon the determinations, it is to be noted that all the genera found occur in the Carboniferous rocks of Europe.[2] Hatch and Corstorphine are also inclined to correlate the Witteberg series with the Carboniferous of the Northern Hemisphere.[3] The Ecca series is of Permo-Carboniferous age, but until more is known about the age of the strata involved in the folding this widespread break in South Africa cannot well be correlated with movements elsewhere. But it would be most natural to suppose that the glaciation (represented by the Permo-Carboniferous Dwyka conglomerate) followed closely upon the deformation.

In North America movements which appear to be contemporaneous with the Hercynian folding of Europe at the close of the Westphalian have been recognized at a number of points. Very pronounced movements affected portions of Oklahoma. The Arbuckle Mountains, which had suffered Culmide folding, were again subjected to strong folding before the close of the Pennsylvanian. Taff states that this deformation commenced near the beginning of Upper Carboniferous time and ended before its close.[4] Hutchison describes the major portion of the present structure of the region of the Arbuckle and Criner Hills as formed in early mid-Carboniferous times.[5] The date of the folding, while occurring some time within the Pennsylvanian period, cannot as

[1] F. H. Hatch and G. S. Corstorphine, *op. cit.*, pp. 335–38; also Plate I, opposite p. 33.

[2] A. W. Rogers and A. L. DuToit, *An Introduction to the Geology of Cape Colony*, 2d ed. (1909), pp. 159–60.

[3] Hatch and Corstorphine, *op. cit.*, p. 344.

[4] J. A. Taff, "Geology of the Arbuckle and Wichita Mountains in Indian Territory and Oklahoma," *Prof. Paper 31, U.S. Geol. Survey* (1904), p. 38.

[5] L. L. Hutchison, *Bull. 2, Oklahoma Geol. Survey* (1911), p. 7.

yet be closely located. But rocks of very late Pennsylvanian or early Permian age have been deposited across the western end of the Arbuckle uplift. They lie in a nearly flat position across the eroded edges of several thousand feet of the Pennsylvanian, all of the Mississippian, Devonian, Silurian, and a large part of the Ordovician rocks.[1] The folding of the Wichita Mountains is thought by Taff to have occurred simultaneously with that of the Arbuckle uplift.[2]

Some movements, though they do not appear to have been very pronounced, affected the extreme eastern border of the continent. In the southeastern part of New Brunswick the strata of the Upper Carboniferous[3] (or Permo-Carboniferous)[4] rest unconformably upon the Millstone Grit at various points. These movements may possibly have affected also the eastern side of the Appalachians farther south, but the intense deformation which developed the Appalachian Mountains, as now known, came later.

In the Appalachian region, according to David White, there is distinct evidence of a shift in the region of sedimentation or, in other words, a change in the direction of warping of the Appalachian trough at the close of the Westphalian time; for during the Westphalian the maximum subsidence and loading was toward the south, in which region no Stephanian was ever deposited, while in the northern Appalachian region, the greater part of which was exposed during most of the Westphalian time, there occurred the maximum deposition of Stephanian with possibly lack of interruption in its passage into the Permian.[5]

In addition to the better-known cases of mountain development, there are several movements of this general age which cannot be placed very closely with the data now at hand. According to Evans, the eastern Andes of Bolivia, which had been folded in very early times and had again been brought beneath the sea, received

[1] J. A. Taff, *op. cit.*, pp. 35–36.

[2] *Ibid.*, p. 80.

[3] R. W. Ells, *Geol. Survey of Canada, Ann. Rept.*, I (1885), 7, 29 E.

[4] L. W. Bailey, "Report upon the Carboniferous System of New Brunswick," *Geol. Survey of Canada*, XIII (1902), 19 M.

[5] David White, personal communication.

renewed elevation late in the Carboniferous period.[1] Kayser is authority for the statement that the folding of the Urals began late in the Carboniferous and reached its height in the Permian, and, even as far as Armenia and central Asia, evidences of folding and mountain-building movements at about this time have been recognized.[2] Farther east, in the southern Tian Shan range, Keidel has recognized pronounced foldings which occurred within the Carboniferous period. The Lower Carboniferous sandstones and shales had been greatly folded and considerably eroded before the Schwagerina-bearing limestone was laid down upon the trunkated folds. The Schwagerina limestone, which is correlated with a similar formation in the Urals, belongs to the uppermost part of the Pennsylvanian.[3] Whether this movement is a Culmide or a Westphalo-Carbonide is therefore not yet determined, but because movements of the latter class were so widespread along this general east-and-west axis it may not improbably prove to belong to this group.

Further studies in the heart of the continent should add much to the subject of Carboniferous diastrophism, for the broad mountainous zone between central Siberia and the Tertiary chains in south Asia is made up of ranges whose principal folding appears to date from about the middle of the Carboniferous period, which suggests that they may be the homologues of the Armorican and Variscan chains of Europe.[4] The Altai and the chains of Trans-Baikalia make up one series so assigned; another begins in the Kuen Lun and follows the Nan Shan to the chain of northern China; and another is the Tsing Ling Shan and the mountains of northern Szechuan where Baron von Richthofen found folding at

[1] J. W. Evans, "Expedition to Caupolican Bolivia, 1901–1902," *Geog. Jour.*, XXII (1903), 633–34.

Isaiah Bowman, "The Physiography of the Central Andes," *Am. Jour. Sci.*, 4th Ser., XXVIII (1909), 376.

[2] Emanuel Kayser, *Geologische Formationskunde*, 2d ed. (1902), p. 174.

[3] Hans Keidel, "Geologische Untersuchungen im südlichen Tian Schan nebst Beschreibung einer obercarbonischen Brachiopodenfauna aus dem Kukurtuk-Tal," *N. Jahrb. f. Min.*, XXII, Beilage Bd. (1906), pp. 282–83.

[4] Emile Haug, *op. cit.*, p. 834.

the close of the Carboniferous, together with great eruptions of igneous rock which were presumably associated with the movements.[1]

### PERMO-CARBONIDES

In the two preceding sections an endeavor has been made to separate the Culmides and Westphalo-Carbonides out of the great group of diastrophic movements that marked the close of the Paleozoic. It remains to assemble the movements that took place following the Permo-Carboniferous sedimentation. But here the time of the diastrophism can be less definitely located, and the correlations less closely made than in the case of the Westphalo-Carbonides. Recognizing this difficulty the term Permo-Carboniferous is quite widely in use in various parts of the world, and as this is in reality a period of transition from the Paleozoic to the Mesozoic, this terminology has its advantages, and the name Permo-Carbonides will be used to designate the final set of disturbances which mark the break between the two eras.

One of the most familiar as well as one of the most pronounced of the Permo-Carbonide movements was the folding of the Appalachian Mountains of North America. The principal folding of the Appalachians followed the laying-down of the Dunkard sediments, which are the youngest strata involved in the folds. The age of the Dunkard beds was identified as Permian by Fontaine and White in 1880,[2] and this has been very commonly accepted since. But David White states that the flora of the Dunkard shows it to be transitional between Carboniferous and Permian, and that its uppermost portion corresponds approximately to the lowest member of the Rothliegende of Europe.[3] This reference of the greater part of the Dunkard to the Lower Rothliegende he believes to be well founded. This would bring the main folding of the Appala-

[1] Bailey Willis, *Research in China*, I, Pt. I (1907), 297.

[2] W. M. Fontaine and I. C. White, "The Permian or Upper Carboniferous Flora of West Viriginia and Southwestern Pennsylvania," *Second Geol. Surv. of Pennsylvania, Report of Progress, PP.* (1880), pp. 105–20.

[3] David White, "Permian Elements in the Dunkard Flora," *Bull. Geol. Soc. Am.*, XIV (1903), 538–42.

chians after the Carboniferous and after a portion, at least, of the Permian, and it may not have followed immediately after the deposition of the Dunkard.

The time of the Appalachian folding seems to have been also an epoch of general epeirogenic movements. At this time much of the eastern half and of the interior of North America was uplifted and aqueous sedimentation largely stopped. Much of this region was never again the site of notable sedimentation.

In South America also a general movement of emergence seems to have been in progress at this time. Katzer places the withdrawal of the sea from the lower Amazon region within the Permian. Schuchert states that the sea retreated from this region "at the close of Neo-Carbonic time," and that thereafter the interior of this extended land, as far as observations will permit judging, was not again subjected to marine deposits.[1]

In Australia minor deformative movements are said to have occurred in New South Wales during the Permo-Carboniferous period, while Süssmilch states that at its close renewed orogenic movements of a more pronounced sort took place in the same region.[2] At this time the folding extended sufficiently far southward to develop a series of broad anticlinal and synclinal folds in the Permo-Carboniferous strata along the northern edge of the Maitland coal field where the folding is believed to have produced an elevation of at least 7,000 to 8,000 feet.[3] The axis of the folding is north and south, parallel to the present coast. This was the last folding in New South Wales; subsequent movements have been of the epeirogenic sort.

In eastern Europe it was not until late in the Permian that folding is said to have taken place on the site of the Russian geosynclinal. All members of the Carboniferous, and some of the Permian, thus form a thick concordant series. In the Donetz basin, the Upper Permian was affected by the folding.[4]

[1] Charles Schuchert, "Geology of the Lower Amazon Region," *Jour. Geol.*, XIV (1906), 725.

[2] C. A. Süssmilch, *op. cit.*, p. 102.

[3] *Ibid.*, p. 121.

[4] Emile Haug, *op. cit.*, p. 834.

The close of the Permian in western Europe seems to have been accompanied by a general uplift. In most parts of England there is a certain amount of unconformity between the Permian and the Bunter, or Lower Triassic, but it does not indicate any great tectonic disturbance, though in the northern and central portions of England there was some tilting of the Permian beds as well as some faulting in the interval.[1] In the Hercynian chain, the last movements took place at the close of the Permian, according to Haug. From them arises the discordance observed in the southern Vosges and in the central plateau of France between the Upper Permian and the Lower Triassic.[2] In the southern portion of the central plateau, especially in the basin of Gard, the most intense foldings of the Hercynian system came after the Stephanian, and in the Alps of Savoy the Permian also is often found to have been included in the pre-Triassic folding.[3]

A Permo-Carbonide movement also affected the southern Tian Shan range in central Asia. The youngest member of the Paleozoic sedimentary series in this region, according to Keidel, is a conglomerate containing pebbles from the Schwagerina (Permo-Carboniferous) limestone formation.[4] This conglomerate has resulted from an upbowing of the range, and associated with it is a discordance. Resting upon the conglomerate are the Angara beds which are classed as Triassic, though Keidel is inclined to believe that their lowest layers should be placed in the Paleozoic. But if diastrophism be followed as the basis of correlation the break between Paleozoic and Mesozoic would naturally come somewhat lower—at the discordance.

## GENERAL

From this brief assemblage of data bearing upon the periodicity of the diastrophism during the Paleozoic era, it appears that the orogenic disturbances of the more pronounced type fall quite generally into distinct groups; that these groups are well separated from one another; and that the disturbances of each group were more or less widely distributed over the globe, and that they had their

[1] A. J. Jukes-Browne, *op. cit.*, p. 215.

[2] Emile Haug, *op. cit.*, pp. 917–18.

[3] *Ibid.*, p. 831.

[4] Hans Keidel, *op. cit.*, pp. 356–57.

active stages at about the same time, so far as correlations now permit one to judge. It appears also from this study, that the current divisions into periods which represent the general judgment of geologists as to what are natural divisions, and which are based on various considerations largely stratigraphic and paleontologic, are in fair accord with the divisions that would be made if diastrophism were chosen as the primary basis of division. Such general accord was to have been expected if diastrophism is a true and fundamental basis for such division, but some divergencies in detail were also naturally to be anticipated.

The chief divergencies that have been found are the debatable division line between the Cambrian and the Ordovician, and the partially accepted separation of the old Carboniferous group into Mississippian, and Pennsylvanian. It is notable that these division lines are those that have been regarded as the least satisfactorily established. Since the famous controversy of Murchison and Sedgwick the Cambro-Ordovician dividing line has been a subject of debate, and of uncertainty and oscillation of judgment. The breaking-up of the old Carboniferous period and the recognition of the lower portion as a distinct period under the name Mississippian is a matter of recent date and is only partially accepted. There is evidence of distinct diastrophism at the close of the Mississippian, but from present data it does not seem to be of the same order of magnitude and prevalence as the deformations that mark off the other periods, with the exception of the mooted Cambro-Ordovician diastrophism.

The Westphalo-Carbonide movement is brought by diastrophic studies into more prominence than was given it under the criteria that have been in common use.[1] It appears to have been unusually widespread and pronounced. On account of its magnitude, dynamically and geographically, it seems entitled, under the diastrophic view, to be made to mark the beginning of the closing scenes of the Paleozoic era. Shortly following it, and perhaps in

[1] De Lapparent, however, states that while formerly it was thought proper to put the coal beds all in one undivided period, one is now forced to observe that the coal formations are traversed, between the Westphalian and the Stephanian, by an orogenic phenomenon of such importance that it should be of greater weight than all else in determining the limit of the systems (*Traité de géologie*, 5th ed., II [1906], pp. 889–90).

consequence of it, came the extraordinary Permo-Carboniferous glaciation, attended by biological changes of so pronounced a nature that they have generally been regarded as the initiation of the distinctive types of life of the Mesozoic era. The Permo-Carboniferous events that followed the Westphalo-Carbonide movement have been growing into recognition in recent years as indicating a time of transition from the Paleozoic to the Mesozoic. These studies give support and definiteness to that idea.

Thus it appears that the division of Paleozoic time on the basis of diastrophism, so far as present data go, does little violence to the systems and time divisions already formed on stratigraphic and paleontologic and other grounds, while it seems to throw distinct light on the remarkable phenomena that closed the era, phenomena over which not a little obscurity long has hung.

# ON THE RELATIONS OF THE GREAT MARLBOROUGH CONGLOMERATE TO THE UNDERLYING FORMATIONS IN THE MIDDLE CLARENCE VALLEY, NEW ZEALAND

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## INTRODUCTION

McKay, in describing the geology of the Cape Campbell district in 1877, mentioned "conglomerates, composed in chief part of well-rounded bowlders, but having a large percentage of angular blocks of great size, so that on the surface they often present the appearance of old Morainic accumulations." His description continues as follows: "A great variety of rocks are represented in these conglomerates—old slates and sandstones, and even crystalline rocks from the inland ranges; volcanic rocks from the Amuri group; green sandstone from the Saurian beds; and great masses of Amuri limestone—as before mentioned large bowlders of conglomerate from the Awatere beds, as well as limestones, sandstones, and shell conglomerates belonging to the same."[1] In the section accompanying McKay's report[2] the deposit is represented as superficial, lying on the upturned edges of the "Saurian beds"

[1] A. McKay, *Geol. Surv. of N.Z., Rep. Geol. Expl. during 1874–76*, p. 190, 1877.

[2] *Op. cit.*, BB, opp. p. 188.

(Cretaceous), and its correlation is suggested with "the high-level shelly conglomerates at Amuri Bluff,"[1] which are probably Pleistocene.

Some years later the same geologist found deposits of similar type, which he regarded as parts of the same formation, at various places in Eastern Marlborough. The most conspicuous and characteristic of these are several outcrops in the neighborhood of Kekerangu,[2] that forming Deadman's Hill,[3] and a long strip in the Middle Clarence Valley.[4]

The beds exposed in Heaver's Creek, Kekerangu, are described by McKay in the following terms:

> They are rudely stratified, at places showing that the beds are standing nearly vertical; in the lower part are enormous blocks of Amuri limestone and masses of soft marly strata, which it seems impossible to convey any distance and deposit in the position in which they are found. Saurian concretions from the Amuri beds, and bowlders containing Awatere fossils, are also plentiful. . . . . It is impossible to give any description which will convey a correct idea of the pellmell manner in which the various materials of this conglomerate breccia are mixed together. Well-rounded sandstone conglomerates are confusedly mixed with angular blocks of all sizes up to 12 ft. or 15 ft. in diameter, divided into thick beds by thin beds of sandy and clay beds, which themselves are not evenly bedded, but twist and wind among the coarser materials as though the beds had been thrown into undulations prior to their being upheaved and subsequently brought into their present position by faulting."[5]

Hector[6] mentions, in the same section, the most finely laminated silts with fossil plants in the midst of the coarse conglomerate.

Both Hector[7] and McKay always regarded the conglomerate as unconformable to the beds on which it rests, and it is thus represented in all their sections illustrating structure in the Clarence Valley and also at Deadman's Hill.[8] In all these cases, it is repre-

[1] *Op. cit.*, p. 191.

[2] A. McKay, *Geol. Surv. of N.Z., Rep. Geol. Expl. during 1885*, pp. 114–16, 1886; *ibid.* (*1888–89*), pp. 169–71, 1890.

[3] *Op. cit.* (*1886*), pp. 116–17; *ibid.* (*1890*), pp. 171–72.

[4] *Ibid.* (*1886*), pp. 118–22; *ibid.* (*1890*), pp. 174–78.

[5] A. McKay, *op. cit.* (*1886*), p. 115.

[6] Sir James Hector, *Geol. Surv. of N.Z., Progr. Rep. for 1885*, p. xxxvi, 1886.

[7] *Ibid.*, p. xvi.

[8] See, for example, Hector, *op. cit.*, p. xxxv; McKay, *op. cit.* (*1886*), pp. 94, 95, 116.

sented as following the Grey Marl, a formation which, in the classification adopted by Hector's Survey, was classed as Cretaceo-Tertiary, i.e., older than Upper Eocene. Since the conglomerate contains bowlders of fossiliferous rock, which McKay regarded as derived from the Awatere beds (believed to be of Miocene age), the reason for regarding it as unconformable to the underlying series is apparent.

It was recognized that the accumulation of the conglomerate took place prior to the earth movements that gave rise to the Kaikoura and Seaward Kaikoura ranges,[1] but one of the lines of argument on which McKay relied to prove his contention was undoubtedly a mistaken one. He argued that, since no beds had been discovered in place in the neighborhood from which the fossiliferous Tertiary blocks in the conglomerate could have been derived, these bowlders had been transported across the site of the Kaikoura Ranges, before their uplift, from a known outcrop of similar rocks far to the southwest.[2]

Recently, however, Thomson[3] has discovered a bed of marine, fossiliferous, Tertiary sandstone, apparently interstratified between two coarse bands of the conglomerate forming Deadman's Hill, which is identical with the material of the blocks in the conglomerate in that locality formerly regarded as exotic. The large bowlders, moreover, in Deadman's Creek (or Shades Creek), the presence of which has been noted by various observers, come in reality from this outcrop of rock in place, and not, as has been supposed, from the conglomerate. The writer has also examined the locality in company with Dr. Thomson. The junction of the sandstone with the underlying band of conglomerate is not clear, and there is a bare possibility that the beds are separated by a fault (or thrust plane). If this is so, the sandstone may be the source of the fossiliferous bowlders in the underlying as well as in the overlying conglomerate beds. Whether this is the case or not, the discovery indicates the danger of assuming that any of the constituents

[1] Hector, *op. cit.*, p. xxxvi; McKay, *Geol. Surv. of N.Z., Rep. Geol. Expl. during 1890–91*, p. 95, 1892.

[2] A. McKay, *op. cit.* (*1892*), p. 4.

[3] J. Allan Thomson, *N.Z. Geol. Surv., 7th Ann. Rep.*, 1913, p. 123.

of the conglomerate are not of local origin because local outcrops of similar rock in place have not yet been found.

The same conglomerates have been described as glacial moraines by Park,[1] who assumes extensive glaciation in Eastern Marlborough in the Pleistocene period.

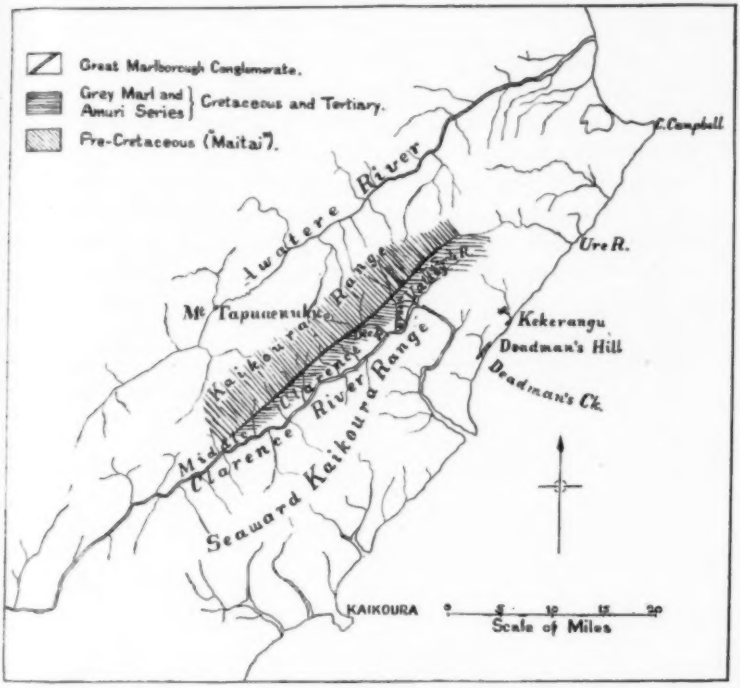


FIG. 1.—Locality map of Eastern Marlborough, New Zealand. Geology after McKay.

The writer has examined several outcrops in the neighborhood of Kekerangu, that forming Deadman's Hill, and also, at a number of points, the strip which follows the line of the Middle Clarence Valley. The outcrop near Cape Campbell was, however, in the limited time available, not found, although a great part of the

[1] J. Park, *Trans. N.Z. Inst.*, XLIII, 520–24, 1910; *Geology of New Zealand*, pp. 201–5, 1910.

area mapped by McKay[1] as conglomerate was traversed, and it therefore appears that the outcrop is much smaller than is indicated by McKay's map. The stratigraphy at Kekerangu and Deadman's Hill is much involved, and, if Dr. Thomson's discovery at Deadman's, already referred to, is excepted, the sections of the conglomerate there exposed throw little light on its stratigraphical relations.

The writer has, therefore, studied in greater detail the strip in the Middle Clarence Valley where, especially in the Dee and Mead gorges, the sections are clearer; and the results are presented in the following pages.

From what has been already said it is clear that our knowledge of the age of the beds is insufficient to warrant the use of the name "Great Post-Miocene Conglomerate" applied by McKay and the formation will therefore be referred to in this paper by the name "Great Marlborough Conglomerate" adopted by Thomson.[2]

## CONCLUSIONS AS TO THE NATURE AND RELATIONS OF THE CONGLOMERATE

Briefly stated, the conclusions as to the nature and relations of the Great Marlborough Conglomerate reached by the writer are as follows:

1. It exhibits fairly regular stratification, always more or less parallel to that of the underlying series.

2. Its relation to the underlying series, wherever the junction has been examined, appears to be one of conformity.

3. It contains, in abundance, masses of rock derived from the underlying formations.

4. It is, in the main, a fluviatile deposit.

The second and third statements, which appear, at first sight, contradictory, may be otherwise stated thus: The conglomerate forms a "superposed series" with the beds on which it rests, but, with an adjoining area of the same beds, which has since been entirely removed by erosion, but which supplied much of the material of the conglomerate, it formed, when first laid down, an

[1] *Op. cit.* (*1877*), map, p. 188.

[2] J. Allan Thomson, *N.Z. Geol. Surv., 7th Ann. Rep.*, 1913, p. 123.

"apposed series."[1] The evidence in favor of these conclusions is set out in the following pages, and also a hypothesis to account for the peculiar features of the formation.

### CONFORMABLE RELATION TO THE UNDERLYING BEDS

In the Middle Clarence Valley the conglomerate overlies the bluish-gray mudstone to which the name Grey Marl is generally applied, and this, in turn, conformably overlies the Amuri Limestone. Wherever examined the Amuri Limestone, Grey Marl,

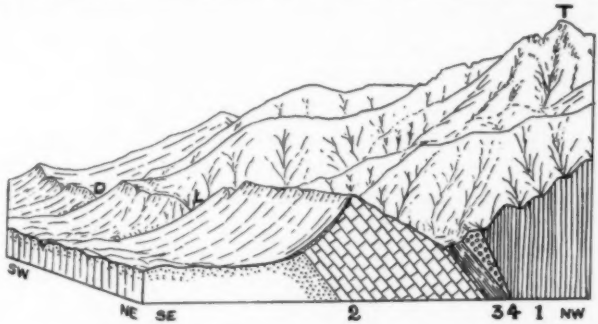


FIG. 2.—Diagram illustrating the occurrence of the Great Marlborough Conglomerate with the underlying Grey Marl and Amuri series in the Middle Clarence Valley, along the base of the Kaikoura Range.

The front of the diagram is a generalized section along the southwest side of the Mead River. (The dip of the fault plane in this section is hypothetical.)

*D*, Dee River; *L*, Limburne Stream; *T*, Mount Tapuaenuku

4, Great Marlborough Conglomerate

3, Grey Marl Series } Cretaceous and Tertiary

2, Amuri Series }

1, Pre-Cretaceous ("Maitai") Rocks. (Structure obscure)

and Great Marlborough Conglomerate have the same strike and dip, striking approximately northeast and dipping at high angles to the northwest, while the conglomerate is terminated upward by a reversed fault which runs for many miles, parallel to the strike of the above-mentioned beds, along the front of the Kaikoura Range, and brings the conglomerate against the old rocks of the range as indicated in Figs. 1 and 2.

In the gorge of the Mead River clear sections are exposed showing the relation of the conglomerate to the Grey Marl. The

[1] Cf. E. Suess, *The Face of the Earth*, I, 378–79 (Oxford, 1904).

junction plane, at the point examined, strikes N. 25° E., and dips at an angle of 47° to the west-northwest. The irregular bedding in the conglomerate is roughly parallel to the junction and apparently the junction is parallel to the bedding of the Gray Marl. In the latter, however, the only indication of stratification is given by discontinuous bands of concretions.

The upper layer of the Grey Marl is, lithologically, very similar to the Grey Marl as a whole except that it contains some broken shells and a few small pebbles or perhaps concretions of material similar to the Grey Marl but more indurated and containing shells in a bad state of preservation. These resemble larger masses, found close at hand, at a somewhat lower horizon, but still near the top of the Grey Marl series, which contain well-preserved fossils.[1] It is not quite clear whether they are derived bowlders or concretions. Thomson regards them as the former and considers that they indicate a certain amount of contemporaneous erosion.

Immediately overlying the upper layer of Grey Marl is a layer, 2 ins. in thickness, of conglomerate formed of various-sized rolled pebbles of graywacke (from the pre-Cretaceous formations). Next follows 2 ft. 6 ins. of bedded sandstone, covered by 1 ft. of mudstone, and that again is followed by many feet of fairly coarse conglomerate interbedded with sandstone and mudstone bands 1 ft. to 3 ft. in thickness, and with bands of very coarse conglomerate.

A distant view of the junction in the Mead gorge gives a false appearance of unconformity with discordance of dip, and led McKay to make the statement: "The overlying conglomerates are quite unconformable."[2]

This appearance of unconformity is due mainly to two causes:

1. Owing to the fact that the Grey Marl is a weak stratum, while both the underlying Amuri Limestone and the overlying conglomerate are very resistant, the valley of the Mead River is contracted into narrow, vertical-walled gorges where it crosses the conglomerate and limestone, but, between the two gorges, it opens out, with broadly flaring sides and a floor of considerable breadth, to form a nearly circular hollow on the outcrop of the

[1] J. Allan Thomson, *N.Z. Geol. Surv., 7th Ann. Rep.*, p. 123, 1913.

[2] A. McKay, *op. cit.* (*1886*), p. 95 and section p. 94.

weaker rock. The junction between the Grey Marl and the conglomerate passes as a conspicuous line up the sides of this basin, and, since the face on which the section is exposed runs for some distance more nearly parallel to the strike than to the dip, the effect is to make the dip of the junction, when viewed from downstream, or from the center of the hollow, appear much more nearly horizontal than it really is. The apparent dip is, owing to the absence of a hard line of division between the Grey Marl and Amuri Limestone, compared by the eye with the true dip of the limestone outcropping in the monoclinal ridge (see Fig. 2), and there is thus produced the effect which was sketched by McKay as shown in Fig. 3.[1] Fig. 4, however, which is a photograph looking along the strike of the junction, shows that there is no appreciable discordance of dip.

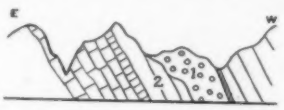


Fig. 3.—Part of McKay's section in the Mead River, showing the junction between the Grey Marl (2), and the Great Marlborough Conglomerate (1).

Fig. 4.—View of the junction between the Grey Marl and Great Marlborough Conglomerate, looking south-southwest across the Mead River.

2. Although the surface of junction between the Grey Marl and the conglomerate was originally plane, it is now broken by a number of small faults, each with a downthrow of only a few feet, which appear to be tension faults formed while the conglomerate and the underlying strata were in their original horizontal position. These, collectively, have let down, by trough-faulting, a wedge of conglomerate into the Grey Marl, giving the surface of junction a somewhat undulating form shown in Fig. 4, in which the faults can be seen.

[1] After McKay, *op. cit.* (*1886*), section p. 94; see also Hector, *op. cit.*, p. xxxvi.

A false appearance of bedding in the Grey Marl, nearly at right angles to the real stratification, is produced by the downward continuation of the faults, veins having been formed along the fault planes, which stand out a little from the bare, denuded surface of the weak marl.

In the Dee River (north branch) there is also a clear section showing the conformable relation between the Grey Marl and the conglomerate, in which the upper part of the Grey Marl is sandy, and contains near the top small pebbles of "Maitai" (pre-Cretaceous) graywacke, up to ½ in. in diameter. Next follow lenticular masses of conglomerate composed of "Maitai" pebbles the largest of which are the size of a hen's egg, and from this there is a gradual passage to the typical conglomerate with sandstone bands.

### COMPOSITION

The writer can confirm, in a general way, the descriptions of the conglomerate, at the various localities visited, as given by McKay, some of which were quoted on an earlier page.[1] McKay, however, in almost every description, reports the occurrence of coarse-grained igneous rocks resembling the intrusives of the Kaikoura Range, which have recently been described by Thomson.[2] These are referred to in the description of the Deadman's Hill conglomerate as follows: "Hornblendic and syenitic rocks brought from the central part of the Inland Kaikoura Range are very abundant."[3] In the Clarence Valley, on the watershed between the Ure and Swale, "abundance of crystalline dyke-rocks derived from the higher part of the Tapuaenuka Range" are reported in the conglomerate,[4] and McKay concluded that the abundant bowlders of igneous rock in the lower Ure River were derived from this source. The writer was unfortunately unable to examine the conglomerate closely at the source of the Ure, but a reconnaissance in the lower

[1] See also, for descriptions of the conglomerate at Deadman's Hill, McKay, *op. cit.* (*1886*), p. 116; (*1890*), p. 171; and for the Clarence Valley, McKay, *op. cit.* (*1886*), pp. 118–22; (*1890*), pp. 174–78.

[2] J. Allan Thomson, "On the Igneous Intrusions of Mt. Tapuaenuka," *Trans. N.Z. Inst.*, XLV, 308–15, 1913.

[3] McKay, *op. cit.* (*1886*), p. 116.

[4] *Ibid.* (*1886*), p. 119.

Ure valley showed that the great majority, at least, of the bowlders of igneous rock in the bed of that river were brought in by tributaries from the northeastern end of the Kaikoura Range where they are present in place. McKay states definitely that these rocks are present throughout a great part of the length of the outcrop in the Middle Clarence Valley[1] and notes their absence only at the southwest end of the strip.[2]

The writer, however, has been forced to conclude, from the results of his own examinations, in which Dr. J. A. Thomson kindly assisted, that igneous rocks of the Tapuaenuku type are absent from the conglomerate at all the points in the Clarence Valley at which it was examined. No such statement can, of course, be made with reference to the conglomerate at the source of the Ure.

The absence of these rocks from the conglomerate in the Dee gorge is especially significant since the intrusions are now exposed in the immediate vicinity and supply the bulk of the bowlders in the bed of the Dee.

The constituents of the conglomerate in the Dee and Mead gorges, as noted by the writer, are as follows:

*In the gorge of the Dee.*—Small well-rolled pebbles of pre-Cretaceous or "Maitai" rocks, both graywacke and jasperoid, are very abundant. Much rarer are lumps of Amuri Limestone of irregular, angular shape, up to the size of a man's head, and there are some pieces of flint, apparently derived from the flint beds which replace the basal part of the Amuri Limestone. Still more rare are lumps of very fossiliferous Tertiary sandstone, and of Cretaceous sandstone containing fragments of *Inoceramus;* these range up to 1 ft. in diameter. The largest blocks, generally several feet in diameter, are of crumbling, sandy marl or mudstone exactly agreeing, lithologically, with the upper beds of the Grey Marl present in place immediately below the conglomerate. All the larger blocks are arranged with their largest flat surfaces parallel to the stratification. There are present also some spherical concretions, 1 ft. to 2 ft. in diameter, resembling those in the Grey Marl. Igneous rocks are represented by bowlders of coarse-grained

[1] A. McKay, *op. cit.* (*1892*), p. 4.

[2] *Ibid.* (*1886*), p. 121.

basic, volcanic rock varying in size, the largest noted being 4 ft. in diameter, and by very rare, small pebbles of a fine-grained, porphyritic rock with small felspar phenocrysts.

Successive bands of conglomerate vary in coarseness, but there is no definite alternation or succession of coarser and finer strata. One conspicuously coarse band which occurs about 40 ft. from the base of the section in the main branch of the Dee is shown in Fig. 5. The large bowlders of which it is mainly composed are derived principally from the younger rocks, but large "Maitai" pebbles, up to 6 ins. in diameter, are present, and there are some rounded bowlders up to 6 ft. in diameter which may be either Cretaceous or pre-Cretaceous.

FIG. 5.—Coarse band in the Great Marlborough Conglomerate in the Dee gorge. View looking southwest.

*In the gorge of the Mead.*—In the Mead gorge the conglomerate is, on the whole, coarser than in the Dee, and here, more than anywhere else where it was examined by the writer, there is a mixture of fragments of all sizes. The very largest are rare, but blocks up to 2 ft. in diameter are common, and about one-third of the bulk is composed of bowlders over 6 ins. in diameter. All of them are water worn and most are fairly well rounded. Small pebbles are very abundant throughout, the majority of them being as small as or smaller than a hen's egg. They are fragments of the hardest of the pre-Cretaceous or "Maitai" rocks, smooth and well rounded, frequently almost spherical. There is in addition, both here and in the Dee, a large proportion of fine, sandy material filling the interstices, and the conglomerate is cemented into a very hard rock. The rocks represented are: large bowlders of the same coarse-grained, basic, volcanic rock that occurs in the Dee section; smaller and much rarer fragments of the fine-grained porphyritic rock also sparingly represented in the Dee; blocks of fine, Tertiary sandstone up to 2 ft. in diameter, crowded with shells and water worn (these

are the bowlders regarded by McKay as exotic, but Thomson[1] refers them to the same source as the possibly derived masses in the Grey Marl in this locality); Amuri Limestone, not very abundant, in blocks up to 6 ins. in diameter, but rarely larger; sandstone blocks of all sizes, some resembling the sandstones of the Cretaceous, others possibly pre-Cretaceous; pre-Cretaceous or "Maitai" pebbles, both graywacke and jasperoid, forming, as already mentioned, the bulk of the finer material. Fig. 6 is a photograph showing the general appearance of the conglomerate in the Mead section. In the Mead and Dee sections, as well as elsewhere, thin bands of sandstone occur throughout the conglomerate. They are referred to in the next paragraph.

FIG. 6.—The conglomerate in the gorge of the Mead. (The hammer handle is 10 inches long.)

### FLUVIATILE ORIGIN

From the foregoing descriptions and from those quoted, as well as from the photographs of the conglomerate outcrops at Heaver's Creek, Kekerangu, and Kekerangu South Head published by Park,[2] it will be gathered that superficially the material resembles glacial morainic accumulations. Park[3] lays stress on the angular nature of some of the bowlders, but no polished or striated bowlders have as yet been described. "Large angular blocks" are certainly present, but it is also true that everywhere the bulk of the conglomerate consists of medium-sized to small pebbles of hard rocks, exceptionally well rounded. This fact was noted by McKay.[4] There is, moreover, almost everywhere a rough sorting into coarser

[1] J. Allan Thomson, *N.Z. Geol. Surv., 7th Ann. Rep.*, p. 123, 1913.

[2] J. Park, *Trans. N.Z. Inst.*, XLIII, Pls. 20, 22, 1910; *Geology of New Zealand*, Fig. 93, 1910.

[3] J. Park, "Marlborough Coastal Moraines," *Trans. N.Z. Inst.*, XLIII, 522, 1910.

[4] See, for example, *op. cit.* (*1886*), p. 115; *ibid.* (*1892*), p. 4.

and finer bands in the conglomerate itself, and fairly regular sandstone bands are universally present. These are clearly exposed in the gorge of the Dee, where the series is well stratified, with bands of coarse conglomerate and fine conglomerate, and thin bands of sandstone. In the Mead gorge a similar stratification is well marked, especially in the higher beds, and here the beds are seen to be lenticular, many of the sandstone beds especially thinning out to a feather edge.

In no case, on the other hand, has a distinct false bedding been noted, nor an arrangement of foreset beds that would indicate beach or delta conditions of subaqueous deposition. The beds were evidently laid down nearly horizontally and such deposition of coarse material appears to be impossible in standing water. It is practically certain, therefore, that the shallowing water of the Grey Marl sea was immediately filled when deposition of the conglomerate began, and that subsequently accumulation went on under subaerial conditions.

The character of the conglomerate supports the view that it accumulated under fluviatile conditions, and it presents many striking analogies with the terrestrial deposits in Owen's Valley, California, described by Trowbridge,[1] who has set out a list of criteria for the recognition of such deposits. Of these criteria the following, which appear to be the most valuable, are satisfied by the conglomerate:

1. In alluvial fans coarse material has a wide distribution as against confinement to a narrow zone near shore in standing-water deposits.

2. Textural range in single exposures is large in fan materials.

3. Fan materials are not in general so well sorted as deposits in standing water.

6. Fan material has a lens and pocket stratification, as against a sorting into more or less uniformly thick horizontal layers, as in lakes or seas.

7. Huge bowlders widely distributed vertically and horizontally in a deposit indicate that it was deposited by running water, and with a large proportion of fine material; that is, they indicate that the material is part of an alluvial fan deposit, except in cases where glaciers have affected it, or where standing waters could have received icebergs, or where basal conglomerates are formed near shore.

[1] A. C. Trowbridge, *Jour. Geol.*, XIX (1911), 706–47.

The continuity of the conglomerate in the Middle Clarence Valley throughout a line of outcrop thirty miles in length indicates that it was there deposited as a piedmont alluvial plain and not as isolated fans. A somewhat similar feature now in course of formation by several rivers, between the Seaward Kaikoura Mountains and the sea, in the vicinity of Kaikoura, constitutes the Kaikoura Plain.[1]

It may be noted that both Hector[2] and McKay[3] expressed their conviction that the conglomerate was of fluviatile origin, but both regarded it as the work of a single river system.

## HYPOTHESIS TO ACCOUNT FOR THE PECULIAR FEATURES OF THE CONGLOMERATE

From the description in the preceding pages it is apparent that the Great Marlborough Conglomerate, in the Middle Clarence Valley, rests conformably on the Grey Marl, and yet is largely made up of material derived from that series and the beds conformably underlying it. Much of the material, moreover, agrees exactly in facies with the beds upon which it rests, and undoubtedly has been transported only a comparatively short distance.

In order to account for the supply of this material it is necessary to assume that a neighboring area was differentially elevated to the extent of perhaps as much as twelve thousand feet (the maximum thickness of the Amuri and Grey Marl series, as exposed in the neighboring Coverham section being estimated by McKay[4] at that amount), without seriously disturbing the horizontal attitude of that portion of the Amuri[5] and Grey Marl series, which, a little later, had the conglomerate deposited upon it, and which, as shown in Fig. 2, is, in part, still preserved.

Of the exact nature of this uplift no information is to be obtained, at least in the present state of our knowledge, from the pre-Cretaceous rocks in the vicinity, for their structure is obscure, nor

[1] See McKay, *op. cit.* (*1886*), p. 126.

[2] Sir James Hector, *op. cit.* (*1886*), p. xxxvi.

[3] A. McKay, *op. cit.* (*1892*), pp. 4–5.

[4] A. McKay, *op. cit.* (*1886*), p. 90.

[5] The Amuri Series as here understood includes the whole of the "Lower Greensand" and "Cretaceo-Tertiary" of Hector's Survey.

from the topography, for the main lines of the relief were determined by an orogenic uplift which took place after the deposition of the conglomerate.[1]

Of the three possible ways in which differential uplift might take place, namely, folding, warping, and block-faulting, the first two seem to be out of the question since the surface of the Grey Marl, in the area where it is preserved, was not appreciably tilted by the movement, and appears to have been neither elevated nor depressed to any extent by it. There remains the hypothesis of block-faulting with the restriction that the uplifted block alone moved.

*Significance of faults in the conglomerate.*—Movement of the nature of block-faulting, giving rise to mountains of the Basin Range type, usually takes place along normal faults,[2] and, for a long period after the main faulting, the formation of small normal faults continues, the younger faults so formed dislocating the fan deposits resulting from the erosion of the earlier fault scarp.[3] The occurrence of numerous small faults dislocating the Great Marlborough Conglomerate and the underlying series is, therefore, of some importance. In the Mead and Dee gorges, and in the gorge of the Limburne, a stream between the Mead and the Dee, the conglomerate, wherever examined, was found to be traversed by a number of faults with small throw. The fault planes are now in some cases nearly horizontal, and in others highly inclined, and the downthrow is fairly often found to be on the opposite side from the hade of the fault plane. If, however, the hade be measured from a normal to the plane of bedding, instead of from the vertical,

[1] C. A. Cotton, "Physiography of the Middle Clarence Valley," *Geographical Journal*, XLII (1913), 228.

[2] The advocates of lateral crustal extension and of some phase of crustal compression as the active agency in the formation of block mountains appear to agree that in most though not all cases the boundary faults hade toward the downthrow direction and that the planes of later movements on approximately the same lines are similarly normal fault planes.

[3] See G. K. Gilbert, *U.S. Geol. Surv., 2d Ann. Rep.*, p. 200, 1882; and *Monograph I*, pp. 340–57, 1890; I. C. Russell, *U.S. Geol. Surv., 4th Ann. Rep.*, pp. 451, 453, 1884; and *Monograph XI*, pp. 274–83, Pl. XXVIIIB, 1885; W. M. Davis, *Bull. Mus. Comp. Zoöl.*, XLII, 129–73, 1903; G. D. Louderback, *Bull. Geol. Soc. Am.*, XV, 322, 1904; A. C. Lawson, *Bull. Seismol. Soc. Am.*, II, 193–200, 1912.

the angle of hade is in no case great and the faults are all normal. There are, therefore, good grounds for the assumption that the faults were formed while the beds still lay in their original position.

One fault on the southwest side of the Dee gorge, which may be taken as an example, is illustrated in Fig. 7*a*. The line of fault, in the section exposed, slopes down to the east-southeast and makes an angle of 75° with the vertical, and a sandstone band in the conglomerate is displaced a distance of 4 ft. toward the east.

In the gorge of the Mead, as noted in an earlier paragraph, the faults are numerous, the fault planes striking about east and west. Fig. 7*b* is a sketch of one of them in the conglomerate gorge, which has a downthrow of 1 ft. 6 ins. to the south, and others are shown in Fig. 4. Very numerous faults can be seen in the Mead gorge passing down through the Grey Marl into the Amuri Limestone, but owing to the nature of these strata, the faults are less conspicuous in them than in the conglomerate.

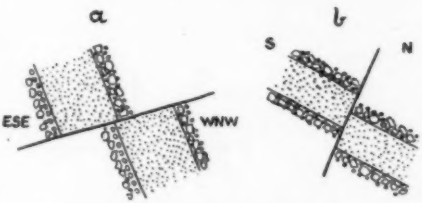


FIG. 7.—Faults in the Great Marlborough Conglomerate.

## GEOLOGICAL HISTORY

During a long period extending from some time in the Cretaceous to well on in the Tertiary, deposition had been going on in the Middle Clarence Valley area under geosynclinal conditions, that is, upon a sea floor that sank gradually during the greater part of the period. Toward the end of the period of deposition of the Amuri Limestone subsidence ceased, and the character of the deposits became more and more argillaceous as the water shallowed. There is thus a gradual passage from the typical Amuri Limestone to the typical Grey Marl. The upper portion of the latter becomes somewhat sandy and contains layers of small pebbles from the old land. The presence of these does not necessarily imply uplift, but slight regional uplift, if it had occurred, would have sufficed to revive slightly the streams of the old land and so to increase

the supply of coarser waste. It is probable that the old land had previously been reduced to senile relief. Slight regional uplift would account for some contemporaneous erosion of the Grey Marl,[1] as it would bring the landward margin of the deposits into the zone of erosion, but it is possible that this is to be explained by slight differential uplift heralding the somewhat later uplift that supplied the material of the Great Marlborough Conglomerate. At this stage the maximum thickness of the accumulations in the geosyncline had reached about twelve thousand feet.[2]

According to the writer's hypothesis, a normal fault was next initiated approximately along or parallel to the line of the great reversed fault previously referred to (see Fig. 2), that was formed during a later period of folding, and now bounds the Clarence Valley on the northwest side, separating the conglomerate from the pre-Cretaceous rocks of the Kaikoura Range. The earlier normal fault, being a line of weakness, may have determined the position of the later reversed fault.

Uplift of the block northwest of the fault plane took place, initiating a period of active denudation along the fault scarp. Some portion of the old land appears to have participated in the uplift, and its revived streams no doubt kept up the supply of well-rolled "Maitai" pebbles which are common in the conglomerate. Some of these, however, may be a rewash of the basal conglomerate of the Amuri Series.[3] The streams from the old land, in their lower courses, crossed the uplifted younger rocks, and, as they emerged from young gorges in the fault scarp, built

[1] Thomson, *op. cit.* [2] McKay, *op. cit.*

[3] Since the above was written the writer has had an opportunity of reading a paper by A. C. Lawson entitled "The Petrographic Designation of Alluvial Fan Formations" (*Bull. Dep. Geol., Univ. Cal.*, VII, No. 15, 1913), in which the name *fanglomerate* is proposed for the class of deposit to which the Great Marlborough Conglomerate belongs. Lawson regards all rounded pebbles in fanglomerate as derived from older conglomerates, and, if it were possible in this case to regard them all as a rewash, both the amount of uplift and the area of the uplifted block that it is necessary to assume would be considerably less than on the hypothesis that they are derived from pre-Cretaceous rocks in place. The writer is not, however, prepared to admit that *all* the small well-rounded material is so derived, although a possible source of supply is the Cretaceous conglomerate (McKay, *op. cit.* [*1886*], p. 90), which locally, at

fans, the material of which was a mixture of angular blocks from near at hand and well-rolled pebbles brought from a distance. The presence of blocks with the facies of the underlying series is thus explained. The bowlders of volcanic rock, while they have not their equivalent in the immediately underlying series, are of the same type as the known volcanics of the Amuri Series which occur a few miles to the northwest in the Awatere Valley,[1] and it is quite possible that they were present in that portion of the Amuri Series that has been denuded off the site of the Kaikoura Range. The absence of the coarse-grained intrusive rocks of the Kaikoura Range, even if these should prove to be absent everywhere from the conglomerate, is not remarkable, and does not necessarily indicate that the date of their intrusion was later than that of the accumulation of the conglomerate. It indicates rather that the rocks of the present Kaikoura Range, which, it must be remembered, owes its present elevation to later folding, had not then suffered the enormous denudation which has exposed the intrusions. It is possible that the bowlders of volcanic rock in the conglomerate represent the more superficial equivalents of the deep-seated intrusions now exposed in the range.

The foregoing hypothetical explanation refers only to the strip of Great Marlborough Conglomerate following the line of the Middle Clarence Valley. The writer believes that the outcrops near the coast may be similarly explained, but further study of them is required, and an extension of the hypothesis to cover all occurrences of the conglomerate is beyond the scope of this paper.

several places in the northeast end of the Middle Clarence Valley, attains a considerable thickness, but is thin as a rule. The pebbles in the fanglomerate, on the other hand, seem to be uniformly abundant, indicating a uniform source of supply. The necessity arises also of accounting for the presence of the rounded pebbles in the transition beds from the Grey Marl to the fanglomerate, the deposition of which must have been contemporaneous with the beginning of movement on the fault plane, that is to say, must have preceded the exposure in the fault scarp of the deeply buried Cretaceous conglomerate. These pebbles at least must have come from the old land.

[1] McKay, *op. cit.* (*1890*), pp. 184–85.

# THE OSTEOLOGY OF SOME AMERICAN PERMIAN VERTEBRATES[1]

S. W. WILLISTON
University of Chicago

## ARAEOSCELIS

A few days before the close of the field trip of the University of Chicago paleontological expedition of 1909, Mr. C. L. Baker, a member of the party, discovered in a ravine near the west line of Craddock's Ranch, near Seymour, Texas, a large lot of loose bones lying on the surface. The spot where they lay was within a hundred yards of the road which probably every collector in the Texas Permian region had traveled many times, but had neglected to investigate, because of its unpromising appearance. The bones lay strewn over a considerable area, and included numerous forms, a list of which, so far as they have been determined, I have given in my *American Permian Vertebrates*. About a bushel of bones and fragments of bones were collected from the surface at this time, including some of the forms under discussion. Early the next season Mr. Paul C. Miller extensively excavated the bone-bed with most interesting and valuable results. At one end of the deposit, a little distance from other bones, though on the same level, he discovered a "nest" of small bones. Occurring in the moist clay and isolated, the bones were first disclosed by the plow, which naturally had a rather disastrous effect upon them, small and delicate as they are. As soon as the deposit was recognized, the pieces of clay containing the loose bones, and the various nodules in which others were inclosed were carefully collected. The closely associated bones of the skeletons were more or less cemented together by a hard-clay nodular matrix, which has been removed with difficulty, the more so because much of the preparation had necessarily to be done under a dissecting microscope. Many of the bones protruded freely from the nodules into the soft clay;

[1] *Contribution from the Walker Museum*, Vol. I, No. 8.

others were wholly free; such bones or parts of bones are in most exquisite preservation. Doubtless had the deposit been discovered sooner and the whole mass brought to the laboratory in a large block, carefully bandaged, there would have been many more bones recovered—bones more or less anatomically associated. As it was, notwithstanding the greatest care, many bones and parts of bones were lost, and others were broken, and their restoration has been especially difficult, since the fragments must be adjusted under a microscope, for the greater part.

The whole collection of skeletons covered only a few square feet, and probably represents a dozen individuals in various stages of growth. It is not improbable that the student intent upon the naming of species and genera would have described these specimens as belonging not only to different species but to different genera as well, had he not known the conditions under which they were found. I think, however, that the remains are all conspecific, notwithstanding the different sizes and degrees of growth which they show. Especially do the smaller, long bones show a lack of ossification at the ends. I have figured parts of the skeleton of several of these specimens, but have not attempted to reduce them all to one scale, which could easily have been done, since the various more or less articulated skeletons give the relations between the different parts of the skeletons. I have made no figures, however, of the bones of the young animals, save of the clavicle, which I cannot find among the more adult bones. In case the future "species splitter" reaches the conclusion that I have lumped several allied species under one name, I may say that the larger specimens of humerus and femur, originally figured, may be considered as the type of both species and genus.

One can only conjecture the reason why so many skeletons of animals of one species in various stages of growth should have been fossilized so closely together. Possibly a group of hibernating animals were suddenly overwhelmed and drowned, or suffocated and afterward covered by water.

I may add, that in the hope of acquiring material for the more complete elucidation of the form, and baffled at first in the interpretation of the skull, I have delayed the full description until

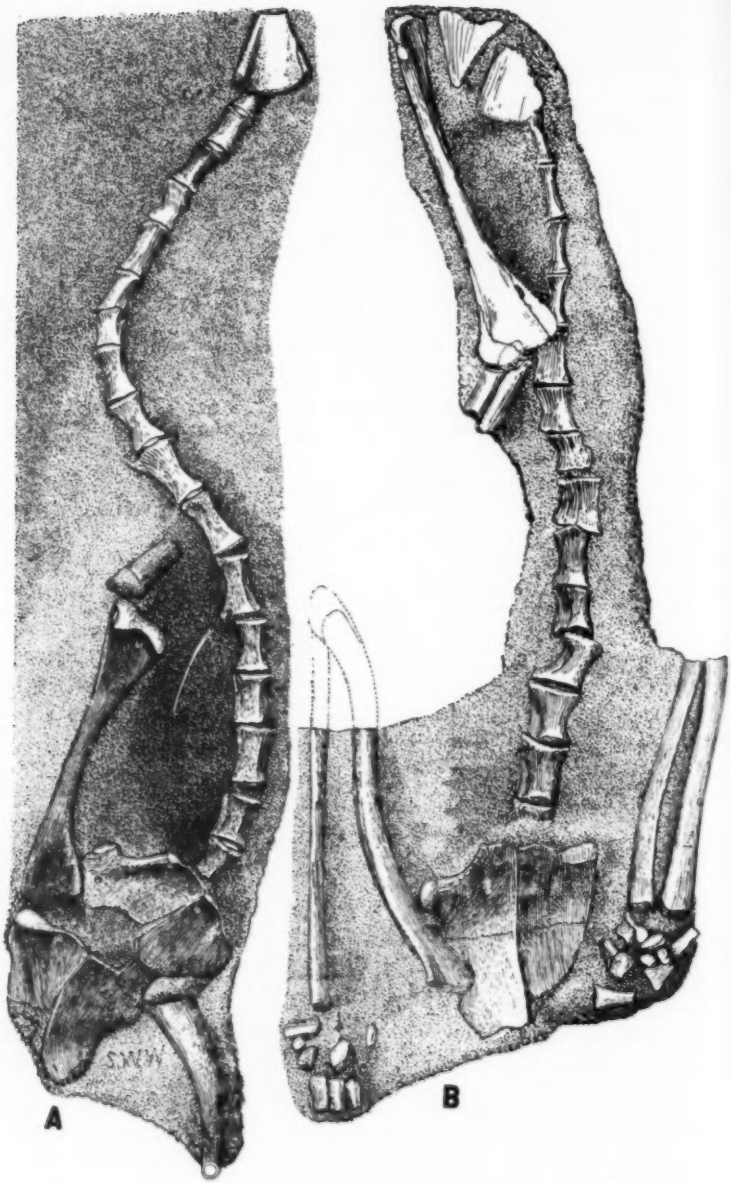


FIG. 1.—*Araeoscelis gracilis* Williston: *A*, part of nearly adult skeleton, as preserved in matrix; *B*, part of adult skeleton, as preserved in matrix. Natural size.

further excavation of the original deposit could be made. Unfortunately, explorations the past year have brought to light only a few more bones, including, however, the skull which has served as the key to the solution of its structure. This delay is the more to be regretted as it has caused Dr. Broom to misinterpret the genus and redescribe it under another name.[1]

## SKULL

The material studied consists of seven skulls, none complete. They are all more or less distorted, with the different elements more or less separated, and in some misplaced and broken. They also differ in size; two preserved in blocks of matrix in association with cervical vertebrae are of adults; the loose ones are all more or less immature, though none is of a quite young animal.

The first specimen studied, at the time I gave the preliminary description of the genus, had the right temporal region exposed, showing conspicuously what seemed to be the smooth border of an entirely open temporal region. Within the depression, however, there is a large flat bone, and the fragment of another, which seemed to be misplaced elements that had been crowded into the cavity. On the opposite side the same free border was visible with the inclosed space filled more or less by matrix. It was because of this apparent structure that I stated in my preliminary description of the genus that "almost certainly there is a large temporal vacuity" and that "nothing definite can be said about *Araeoscelis* till the skulls have been cleaned and studied, and possibly not even then, save the presence of a temporal vacuity."

Unfortunately for my first belief, when the matrix was removed from the left temporal region of the above-mentioned skull it too was found to have a broad expanse of bone at its bottom, filling out nearly the whole space, definitely proving that the bone of the opposite side belonged where it was found. Nevertheless, distinct evidence of a free border above, and the whole structure of the skeleton so definitely uncotylosaurian, made it difficult for me to

[1] *Araeoscelis gracilis* Williston, *Jour. Geol.*, XVIII (1910), 518; *American Permian Vertebrates* (1911), p. 6; *Jour. Geol.* (1913), p. 743; *Science*, November 9, 1913; Huene, *Morph. Jahrb.*, 1912 (not *Araeoscelis* Schultz, 1911); *Ophiodeirus casei* Broom, *Bull. Amer. Mus. Nat. Hist.* (1913).

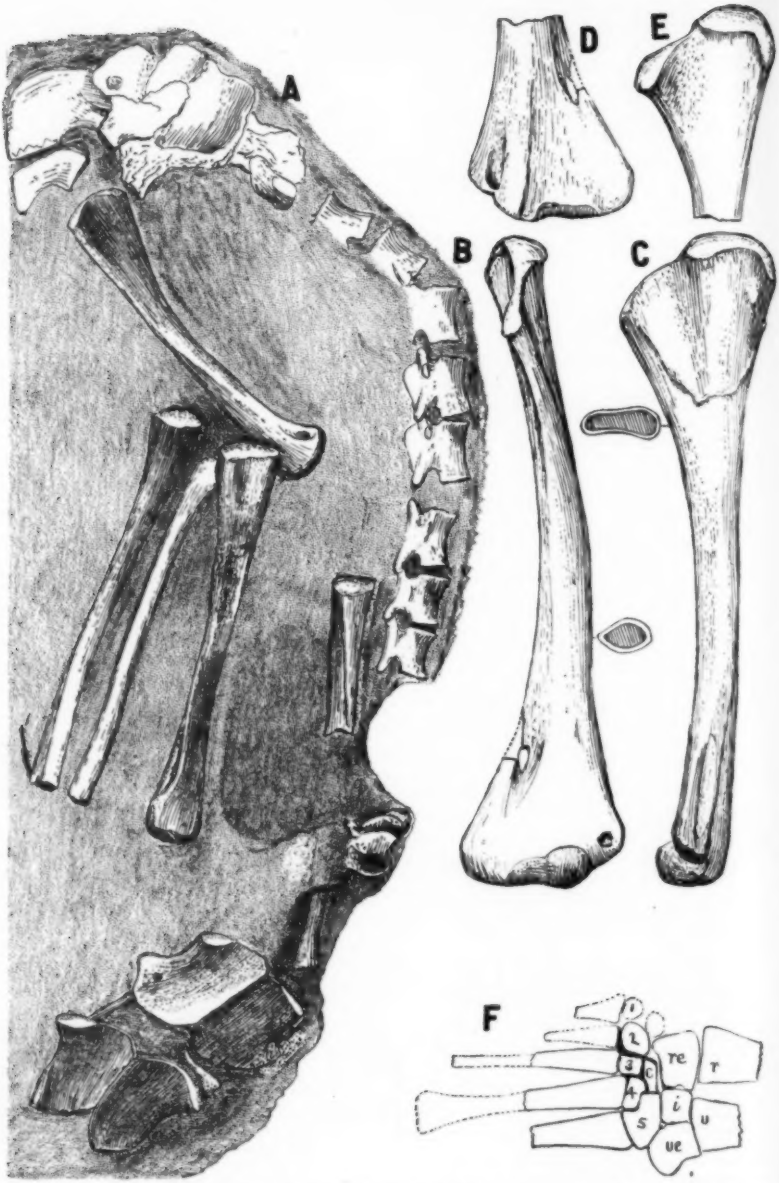


FIG. 2.—*Araeoscelis gracilis: A*, part of young skeleton, as preserved in matrix; *B*, left humerus, adult, ventral side; *C*, the same, radial side; *D*, distal end of another left humerus, ventral side; *E*, proximal end of smaller humerus, ulnar side; *F*, part of left front foot. All except *A* enlarged one-half.

believe that the temporal region was closed in. I spent many hours in the endeavor to reach an understanding of the temporal structure, which appeared to be so inconsistent with that of the remainder of the skeleton. That there was only an upper temporal vacuity did not at this time occur to me, since we know of no other paleozoic reptile having such a structure. I had almost despaired of the solution of the riddle when an additional skull was found which shows on the left side the temporal region in an almost perfect condition. With this specimen as a key, the structure of the skull was readily and completely unlocked.

The drawings of the skull herewith given (Fig. 3, *A*, *B*) are composites derived from all the different specimens, though chiefly based on one of about two-thirds adult size. Nearly every character shown or described has been corroborated by several specimens; in the palate only, less corroborative material is available.

In only one specimen is there anything of the premaxillae preserved. In the reconstruction of the general form of the skull I believe that the figures are tolerably accurate, though I cannot be sure that the skull may not have been a little wider or narrower or higher than I have shown it. It is difficult to make exact measurements of such small bones. The preparation of the specimens has required very patient work with a fine needle under a dissecting microscope, for the most part, but the bones, when carefully prepared, come out clean and smooth.

The *parietals* are longer than broad. In one excellent specimen found later, the distinguishing suture in front is clearly shown. The parietal foramen is large, as shown in three skulls; it is situated toward the front part of the parietals, just a little behind the posterior margins of the orbits. Posteriorly, the parietals are produced into an acute angle in the middle, projecting slightly over the supraoccipitals. I can find in no specimen the slightest indication of a distinct dermosupraoccipital, on the upper surface of the skull at least. On the posterior outer angle each parietal is produced into a slender process, as in lizards. In two specimens, the articulating tabulare was cleanly removed, showing a striated sutural surface near the angle. The arch thus formed, of parietal

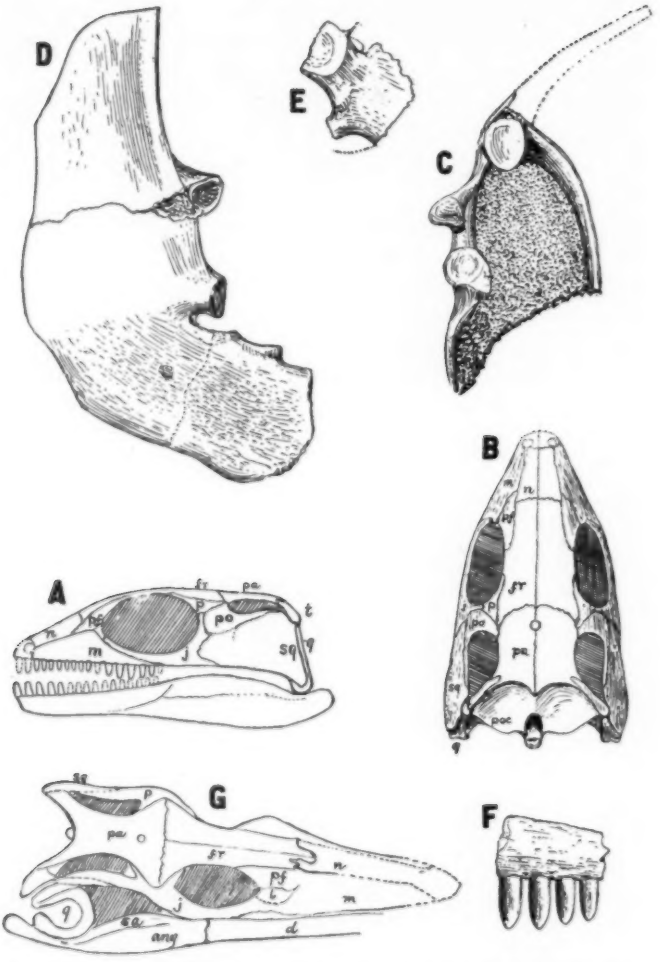


FIG. 3.—*Araeoscelis gracilis:* *A*, skull, about adult size, from the side; *B*, the same, dorsal side; *m*, maxilla; *n*, nasal; *pf*, prefrontal; *pa*, parietal; *poc*, paroccipital; *t*, tabulare; *sq*, squamosal; *q*, quadrate; *po*, postorbital; *p*, postfrontal, *j*, jugal; *C*, left scapulacoracoid, from behind, as preserved in matrix, enlarged one-half; *D*, the same, from the side, the upper end extended in same plane; *E*, part of another scapula; *F*, first four maxillary teeth, much enlarged; *G*, *Opetiosaurus* Kramberger, skull, from above.

and tabulare, is slender throughout, slightly dilated at its extremity, and is directed outward and backward at an angle of about 45 degrees with the long axis of the skull; it is gently curved downward at its extremity to articulate with the squamosal, quadrate, and paroccipital. There can be no doubt of the separation of the element forming the chief part of the arch; I identify it as the *tabulare*. I think that my reasons for so doing are valid. The tabulare in the early reptiles and amphibians is always associated with the outer end of the paroccipital. The only other element that could possibly be in this position is the so-called supratemporal or suprasquamosal. That the present bone is the supratemporal of contemporary authors is, I think, very improbable. This bone is never known to be in relation with the paroccipital and quadrate, relations that the tabulare invariably has; it always articulates with the postfrontal or postorbital when present. I think that doubt of its identity may be dismissed here; it is indisputably the tabulare or "epiotic."

It is now nearly ten years since I wrote the following:

> I prefer to call the bone articulating with the postorbital [in the lizards] the squamosal, the bone which in other reptiles articulates with the postorbital behind. Of course if this is the real squamosal, the posterior element cannot be the squamosal. . . . . The inner part of the so-called squamosal in the mosasaurs [the posterior bone of the arch] corresponds quite well with the outer part of the paroccipital or opisthotic element, which was not found by Parker in the lizard embryo. Referring now to the figures it will be seen that the outer part corresponds fairly well with the bone called the "epiotic." . . . . It may be objected that the presence of an epiotic bone [tabulare] in the lizards is a far too primitive character, but we are now quite certain that the lizards are an exceedingly old group, probably dating from the Permian, and that they have not a few primitive characters,"[1] etc.

The condition of this bone in the mosasaurs is such that one might easily conceive that it is a compound bone formed by the outer part of the paroccipital and the tabulare fused together, though I no longer believe that any part of it is the paroccipital. It was Cope who insisted that the bone in the mosasaurs is the paroccipital only, a view that was vigorously combated by Baur. This view, that the bone is the tabulare, I have consistently held

[1] Williston, *Biol. Bull.* (1904), p. 190.

ever since, though it is only very recently that any other writer has accepted my contention. Three years ago I again expressed my opinion as follows: "I have long believed that the small element intercalated between the paroccipital and the so called squamosal of the lizards corresponds to the epiotics of the stegocephs,"[1] etc.

In front of the parieto-tabulare arch the side of the parietal is concave and free, forming the upper, inner margin of a typical supratemporal vacuity. It was this free border, seen in two specimens, which convinced me originally of the presence of a temporal vacuity in the skull of *Araeoscelis*.

The relations of the *postfrontals* and *postorbitals* are shown in four specimens. The postfrontal is a small bone which forms the upper, posterior border of the orbit, extending forward on the frontal margin not quite to the middle. Below, near the middle of the postorbital, it unites by a slender squamous underlap with the slender postfrontal process of the jugal. In five different specimens this suture is seen, but more positive evidence is furnished by another in which the jugal had been separated a little distance from the postfrontal, showing the delicate striated sutural surface for their union. The postorbital unites with both postfrontal and jugal by a convex suture, which approaches near its middle very near the orbital margin. Above, the postorbital reaches narrowly to the parietal, back of the postfrontal. In one specimen these bones have been separated from the frontal and parietal, leaving the striate sutural surface free. Below, the somewhat thinned anterior part of the postorbital extends downward between the jugal and squamosal at least a third of the way to the lower margin of the arch. Although in one specimen the lower border seems to be complete, I cannot be quite sure of its extent. From this expanded anterior part the bone contracts to extend more and more slenderly very nearly to the tabulare, thus forming nearly the whole of the outer border of the temporal vacuity. Along its whole lower border it is suturally united with the squamosal. These relations are corroborated in so many specimens that there cannot be the slightest doubt on the subject.

[1] Williston, *Amer. Jour. Anat.* (1910), p. 82.

The *squamosal* is a flat and thin bone which fills out the broad expanse of the sides of the skull back of the jugal. It has a very slender connection with the outer border of the quadrate above, and extends downward very nearly to the cotylar margin. At its upper angle, just back of the hind end of the postorbital, it has a facet for union with the tabulare. Below, the bone forms nearly the whole of the lower margin of the arcade. I can find no evidence of a distinct quadratojugal; if such a bone was present it is so firmly fused with the squamosal as to be indistinguishable in any one of the four sides in which the squamosal is preserved nearly entire. In front the bone reaches forward to the hind border of the jugal in one case; in others the anterior part is deficient, so that I cannot be quite sure of the relations here of postorbital and squamosal. It is not impossible that my identification of tabulare and squamosal may be contested—there has been such a vast deal of speculation about the temporal arches that one must expect more—and that what I call the tabulare may be declared to be the squamosal and my squamosal the quadratojugal. But, inasmuch as such an interpretation will be speculation purely and impossible of proof, I am not disturbed by the possibility.

The *quadrate* is more or less exposed in three cases; in one it is nearly wholly exposed on the front side. It is expanded, somewhat fan shaped above, and is thinned. It is visible on the outer side narrowly behind the squamosal attachment. It articulates with the end of the tabulare above, with the paroccipital on the inner side, and with the squamosal on the outer side, as described for that bone. Just above the cotylar margin there is a free, concave surface, bridged over possibly by the lower part of the squamosal. If so, there would seem to be a small quadrate foramen here, arguing the presence of a quadratojugal bone. But I do not think that the evidence is conclusive. The quadrate stands somewhat obliquely, with the outer, gently curved, and thicker margin forming the posterior border of the temporal region; its anterior border is directed forward and inward, and is continuous with the posterior process of the pterygoid. Just how much of this part is pterygoid and how much quadrate I cannot say.

The *jugal* is well preserved in two specimens, completely so in one, with the postfrontal process broken away in the other; a third specimen shows the posterior process. It is a long, narrow bone, which borders the whole lower side of the orbit. It sends a short, pointed process backward to articulate below the front part of the squamosal. The process which is directed upward to meet the postfrontal and postorbital is broader, ending in a slender projection on the front side which overlaps narrowly the postfrontal in front of the postorbital. Posteriorly above it also meets the lower part of the anterior expansion of the postorbital. The anterior end extends nearly to the extreme front end of the orbit, bordering for a long distance the upper side of the maxilla. The bone forms the free margin of the arch back of the maxilla for only a short distance.

The *frontals* are moderately broad and rather long bones, evidently flat or gently concave between the orbits. In most specimens they are pressed more or less together, but, by excavating one of them, I have determined its precise shape. It forms the orbital margin for only a short distance between the ends of the postfrontal and prefrontal. The frontonasal suture is a little before the front end of the prefrontal.

The *prefrontals* are visible in part or wholly on four sides. They are large, triangular bones, projecting outward somewhat in front of the orbit. They extend back narrowly along the frontal margin to within a short distance of the anterior end of the postfrontals.

The *maxillae* are unusually broad bones for a Permian reptile. Each articulates with the nasal in front, excluding the lacrimal from the nares. It is more or less complete in four cases. It terminates posteriorly in an acute point a little before the hind border of the orbit, and is bordered to its highest elevation by the slender jugal. A small space is left between the end of the jugal and the prefrontal in which there may have been a small *lacrimal*, but this bone cannot be distinguished with certainty in any specimen.

Of the *premaxillae* I can say but little. In only one of the specimens can I detect any vestige of it. In one skull, however, the

mandibles are preserved in position with the maxillae entire, showing that the premaxillae must have been small, with not more than two teeth in each.

The *occiput* is clearly distinguishable in two skulls, and partially so in a third. It has a smooth declivity on each side between the angular median projection and the foramen magnum on the inner side, and the parietal arch on the outer side. The surface, descending nearly to the lower border of the foramen magnum, is clearly distinguishable from the dorsal surface and the tabulare, although no distinct post-temporal vacuity is visible; probably in life there was a small vacuity here, which has been obliterated by the depression of the arch. At the outer side the thin bone abuts against the distal end of the tabulare, and thus must come in contact with the upper end of the quadrate. I can distinguish no sutural divisions on this surface, though doubtless it must be formed by the supraoccipital, paroccipital, and exoccipital. I am very skeptical of some of the recent interpretations of the structure of the occipital region of certain American Permian reptiles. It cannot be said too emphatically that only under the most exceptional circumstances can sutures be determined with any degree of certainty from single specimens. The foramen magnum is large; the occipital condyle is hemispherical.

The details of the palate are less certainly determinable. There is an interpterygoidal vacuity, with low, conical teeth along the pterygoids and vomers in front. One specimen shows an indication of a median parasphenoid. The downwardly prominent portion corresponding to the transverse bone—if it be distinct—is armed with five conical teeth of a size nearly as large as those on the anterior part of the maxilla; this elevation joins the maxilla just back of the teeth. Back of these transverse rows of teeth there is an elongated basisphenoid, with a shallow cavity in the middle and a low basisphenoid tuberosity on each side at the end of a lateral elevation.

The teeth of *Araeoscelis* either are variable or the material that I have assumed to belong to a single species comprises more than one. Without better evidence to the contrary, however, I shall assume that the differences which they present, like those of the

skeletal bones, are merely ontogenetic or individual. Typically—that is, those adult skulls associated with the largest vertebrae, and doubtless belonging with the largest humeri and femora—there are fourteen teeth in the maxilla, with the shapes as shown in the illustrations (Fig. 3, *F*, *A*), that is, with the first four rather slender and of nearly equal length; the next four are a little broader at the base, though but little longer; with the ninth they increase in size, both in length and breadth, reaching the maximum in the twelfth; the thirteenth and fourteenth decrease a little in length. Possibly there is a smaller one beyond these, but if so, I cannot distinguish it. This is the condition in both maxillae in one specimen lying in the matrix, in which the teeth have not been injured in preparation. In another skull the number of teeth is the same, but the ninth to the eleventh are not noticeably larger than the preceding ones. In a third specimen, one of the larger ones, I count fourteen teeth in the maxilla, but the last three are small. Finally, in still another specimen, comprising only the maxilla, mandible, face, and anterior palatal bones, fifteen teeth are preserved in the maxilla, with an alveolus for at least one more, and probably alveoli for two more. These teeth, moreover are all smaller than in the other specimens and are of uniform size throughout. The teeth are all simple, without accessory cusps of any kind. They are somewhat wider at the base than long anteroposteriorly and are beveled on the inner side. They are somewhat flattened on the outer side and are obtusely pointed. They are thecodont or protothecodont.

This description in the main seems to agree with that given by Broom[1] of *Ophiodeirus*, though some effort is required to understand his description. One does not feel sure, for instance, what the antecedent of "it" is in the twentieth line of his description of the teeth, but I assume that it refers to *Ophiodeirus*. In the typical *Araeoscelis* it is the last or sixteenth tooth of the series which is smaller, while in *Ophiodeirus*, if I understand the description correctly, the fourteenth, fifteenth, and sixteenth teeth are smaller. He also described the teeth of *Ophiodeirus* as cuspidate; they are not at all so in *Araeoscelis*.

[1] *Bull. Amer. Mus. Nat. Hist.* (1913).

The question of the relationship of *Araeoscelis* to *Bolosaurus* has been raised by Broom in the paper cited. He believes that all three genera, *Bolosaurus*, *Ophiodeirus*, and *Araeoscelis*, are closely related members of the Bolosauridae of Cope. The genus *Bolosaurus* was originally described by Cope from a fragmentary skull, of which the only distinguishable character is found in the teeth These are remarkable, formed as they are of a low crown, with a sharp principal and a low accessory cusp. The type specimens were later studied by Case who referred them to the Cotylosauria, as had Cope, and as did Huene also later. With these typical specimens Case later associated other imperfect ones discovered by himself, describing them, so far as his material sufficed, as *Bolosaurus striatus* Cope. With these later skulls Case provisionally associated a number of vertebrae and fragments of limb bones, but with no assurance, as he expressly stated, of their actual identity—they were merely found in the same bone-bed and he could refer them to no other known form. Had he followed the more usual rule of paleontologists he would have described them as new and left to others the problem of their identity! This caution, however, was not imitated by Broom, who referred all these remains to one species without question of possible distinction, notwithstanding Case's warning.

He distinguishes very properly the skeletal bones from *Bolosaurus*, of which nothing is known with certainty, under the name *Ophiodeirus casei* Broom, but recognized their relationship and possible identity with *Araeoscelis*. I had hoped that the time was past in vertebrate paleontology when genera and species were named on the mere possibility of validity. There can be scarcely a doubt that, aside from the skull, the bones described by Dr. Broom as of *Ophiodeirus casei* are those of *Araeoscelis gracilis*, and in much probability the discrepancy of the skull is due to error.

## VERTEBRAE

The precise number of cervical vertebrae (Fig. 4, *A*, *C*, *E*) cannot be determined. The probability is seven, though there is the possibility of a larger number. The atlas has not been recognized, nor is its loss surprising, since the bones composing it must

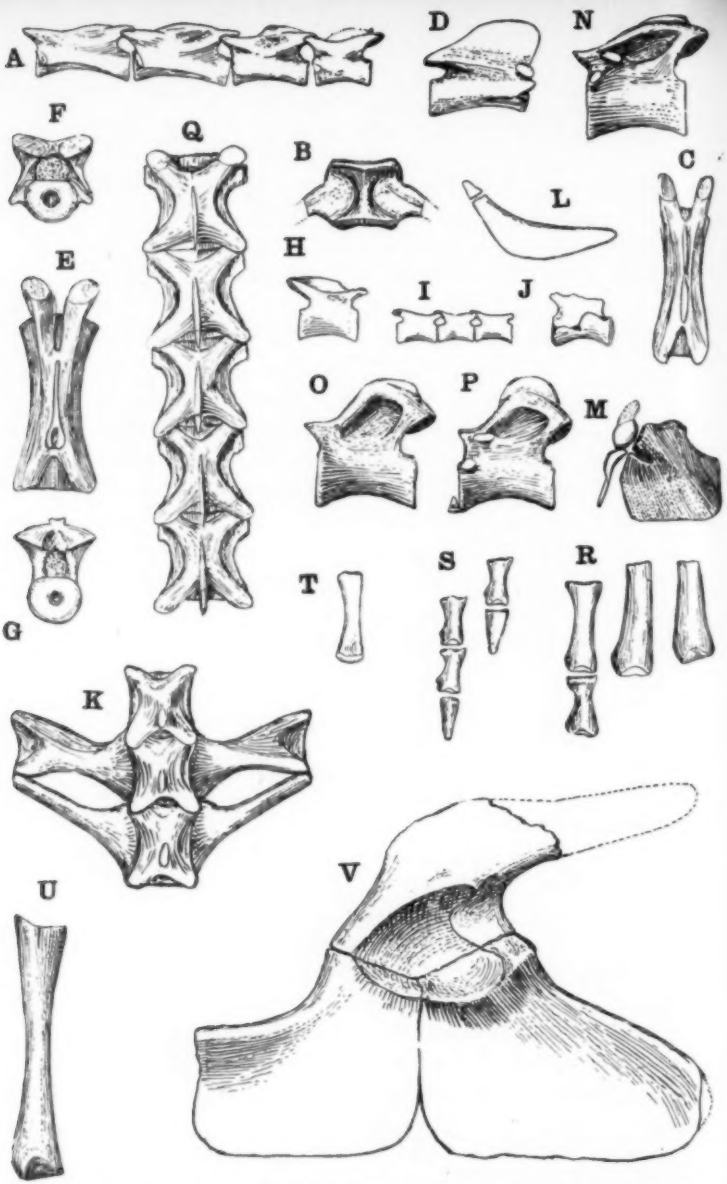


FIG. 4.—*Araeoscelis gracilis:* *A*, posterior cervical vertebrae of young, as connected in matrix; *B*, second caudal vertebra, from below; *C*, fourth or fifth cervical vertebra, from above; *D*, axis, from the side; *E*, median cervical, adult, from above; *F*, proximal end of same; *G*, distal end of same; *H*, median caudal, from the side; *I*, distal caudals, from the side; *J*, median caudal, from the side; *K*, first presacral and sacral vertebrae, not quite adult, from above; *L*, clavicle of half-grown animal; *M*, calcaneum, adult; *N*, dorsal vertebra, adult; *O*, lumbar vertebra, adult; *P*, anterior dorsal, adult; *Q*, series of anterior dorsals, adult, from above; *R*, metacarpals and phalanges of third, fourth, and fifth digits, as preserved in matrix; *S*, phalanges in positions as preserved; *T*, metacarpal or phalange; *U*, fourth metatarsal, adult; *V*, pelvis, adult, from the side. All enlarged one-half.

have been almost microscopical in size, and in none of the specimens has the neck been preserved complete.

A very perfect axis has been found among the loose material. It is shown in Fig. 4, *D*. It doubtless belongs with one of the larger, but not largest, skeletons; probably with the vertebrae shown in Fig. 4, *C*. It measures just 8 mm. in length, and differs markedly from any axis hitherto found in the American Permo-Carboniferous deposits. It has a rather high, thin spine of more than half the length of the centrum, its border sloping downward from above the middle of the centrum to divide into the two postzygapophysial processes. The anterior zygapophyses are unusually large, indicating a large atlantal arch. They are oval and are situated one on each side of the base of the spine, their faces looking upward and outward. The anterior end of the centrum is concave; it is rather narrow, and has an obtuse, keel-like process below; on each side there is a winglike process continuous with the front surface for the attachment of the cervical rib. The plane of the front end is at a considerable angle with the long axis of the centrum. The postzygapophyses are strong, but do not project far beyond the centrum. The centrum has a strong keel below in front, becoming linear posteriorly. The posterior surface of the centrum is nearly circular in outline, and is at right angles with the long axis. In the middle is a deep pit, which doubtless extends through the centrum.

Four posterior cervicals are associated in one specimen, belonging with one of the smaller skeletons. They are shown in Fig. 4, *A*. The first two of these are of nearly equal length; they are elongate and slender. On the side of the centrum in front there is a winglike projection with a facet, as shown in Fig. 4, *A*, for the articulation of a small, single-headed, cervical rib. Leading backward and downward from this facet there is a distinct ridge, which becomes obsolete before reaching the hind end of the centrum. In the middle of the centrum below there is a sharp, narrow keel. The prezygapophyses are more prominent than the posterior ones; their articular surface looks almost directly dorsad. The third vertebra of this series is not only shorter but it lacks the oblique ridge from the costal facet. The fourth is still shorter, and has

a tuberculiform parapophysis, but does not have a diapophysis on the side of the prezygapophysis, and hence must be considered a true cervical.

A second connected series of cervicals, of somewhat larger size, includes three elongated vertebrae, of nearly equal length. I cannot distinguish the posterior two from the anterior two of the preceding series, and the first of this series is scarcely different, save in having a little more pronounced spine on the posterior half of the arch rising directly above the level of the zygapophyses. The two series thus fix the number at not less than seven, four of which are much elongated, and the fifth only a little less so. This, however, does not preclude the possibility of a larger number of vertebrae in the neck. Among the free cervical vertebrae are four elongated ones of adult size, one of which is shown in Fig. 4, *E*, *F*, *G*. There are also several others like these, but of smaller size, one of which is shown in Fig. 4, *C*. They all have rudimentary spines, very thin, short, and low. In some, there is a very small cartilaginous surface on the upper margin. The cervical vertebrae were originally described by me as caudals, but the error was immediately recognized when the connected series were prepared.

*Dorsals.*—In the three specimens shown in Figs. 1 and 2 the dorsal series of vertebrae are complete and connected except that a few have been dislodged in the specimen presented in Fig. 2, *A*. Unfortunately in all three specimens the matrix has been removed from the ventral side, and it would be a matter of much difficulty now to clean the dorsal side and thus to determine the transition from the cervicals to the dorsals. Inasmuch as in two of these specimens the scapulae lie in relation to the nineteenth or twentieth presacrals, that number may be accepted as almost certain for the dorsal series.

Several other series of dorsal vertebrae showing the dorsal side have been prepared. A part of one of these series is shown in Fig. 4, *Q*, from above; and two isolated dorsal vertebrae are shown in Fig. 4, *N*, *P*, together with a more posterior one, a lumbar, in Fig. 4, *O*. The dorsals, as seen from below, are all rather slender; from above they appear less so, because of the overhanging arch. The centra are all more or less obtusely keeled below. An anterior

dorsal is shown in Fig. 4, *P*. In this vertebra the spine is more elevated than it is farther back; in much probability the spine is yet higher in the more anterior dorsals. The spine is thin, and has no tubercular projections of any kind. Another rib-bearing vertebra is shown in Fig. 4, *N*, with a less pronounced spine. The posterior zygapophyses overhang the centrum at a considerable elevation and there is, as in all, an excavation in the sides above. The articular processes for the rib form two surfaces separated by a distinct interval. The diapophysis is on the arch just back of the anterior zygapophysis; it projects but little or not at all beyond the margin of the zygapophysis. The facet for the capitulum is shown in several specimens as a small surface near the front end of the centrum, high up; whether it is on the arch or the centrum cannot be said, but it appears to be on the former. A series of five lumbar vertebrae, in all probability a part of the same skeleton as that to which the figured dorsals belong, differ in their somewhat greater stoutness, and in the entire absence of any diapophysial process or facet; the spine is also vestigial. One of these vertebrae is shown in Fig. 4, *O*.

*Sacrum* (Fig. 4, *K*).—The two sacral vertebrae and a connected lumbar were found in one specimen closely attached to the inner side of the left ischium. The sacral ribs on one side have been worked out fully, and on the other partly. The dorsal arch unfortunately had been injured somewhat. The sacral ribs are long, and those of the second vertebra very slender. They resemble so closely those of some lizards that it is needless to describe them further. As is seen, the first one has an expanded extremity and bore nearly the whole support of the ilium; the posterior one projects markedly forward.

*Caudals*.—Numerous caudal vertebrae are preserved isolated. One of a series of three proximal vertebrae is shown in Fig. 4, *B*, from below. The co-ossified ribs or transverse processes are elongate; none is preserved entire; they turn backward, as usual. More posterior caudals have tubercles on the sides for the posterior ribs. A yet more posterior caudal is shown in Fig. 4, *H;* it has a slight, thin spine on the posterior half, scarcely rising above the level of the zygapophyses. Three found attached in the clay matrix

are shown in Fig. 4, *I*. They are quite like the usual distal caudals of other reptiles. Although the entire number of caudal vertebrae cannot be determined, even approximately, the structure of the numerous isolated vertebrae preserved indicates decisively a long and slender tail. A median caudal of a young animal, shown in Fig. 4, *J*, is of interest because it is the only vertebra in the collection which shows any indication of the suture between arch and centrum.

### PECTORAL GIRDLE AND EXTREMITY

Of the pectoral girdle nothing has been detected of the *interclavicle* in any specimen, and of the *clavicle* only one specimen has been discovered, that of a young animal not more than half adult size, as indicated by the associated long bones in the matrix. This bone is shown in Fig. 4, *L*, as it lies on the matrix in one plane. Its concave border is a little thickened, the convex thin; its scapular extremity is a little thickened, as shown by the section at the broken end. The bone has an unusual shape for a Permian reptile, as might be expected from the unusual shape of the scapula.

The *coraco-scapula* (Fig. 3, *C*, *D*) is of remarkable structure, so unlike anything I am acquainted with among reptiles that I was puzzled at first to interpret it. One complete specimen was found in an isolated nodule, overlapped on its coracoid border by a fragment of the opposite side. In order that the complete structure may be seen, this fragment has been sacrificed. The specimen seems to be quite perfect and undistorted, save that the upper part was smoothly broken and turned over the lower, as shown in Fig. 3, *A*, from behind. In Fig. 3, *C*, I have shown the whole bone as in one plane, though doubtless the upper part was curved strongly inward in life, perhaps more than I have indicated in the dotted line. The postglenoid facet is smooth, rounded, and gently concave; its face looks directly outward from the plane of the coracoid. The preglenoid facet of other Permian reptiles is divided into two very distinct processes, separated by a considerable space, in which there is a smooth, rounded border. There can be no possibility of error in this, since two other fragments, one of which is illustrated in Fig. 3, *E*, show the same peculiarities. Nor can

I find any trace of a supracoracoid foramen; a notch below the lower preglenoid process may represent the vacuity for the passage of the artery. An opening corresponding to the supraglenoid foramen seems to be present just above the supraglenoid articular surface. Apparently the suture distinguishing the coracoid in front is seen in a division across the bone, which I have indicated by a dotted line; but I cannot find the least trace of an anterior suture.

Doubtless the scapula proper must include all that part above the upper facet; possibly the lower preglenoid process is on the anterior coracoid, if there be such a bone in this scapula. At the upper end the scapula is rather narrow, with a thin front border, and a thickened posterior border. If the two coracoids met along the middle line, the blade of the scapula must have projected strongly forward. But that is improbable. Probably the two sides approximated each other only at the posterior end, leaving a large V-shaped interval between the anterior borders, partially filled out by the clavicles and interclavicle.

*Humerus.*—Three complete humeri are preserved free (Fig. 2). Two other complete ones, of a somewhat smaller size, are preserved in the matrix, associated with skeletal bones; and there are various other parts of juvenile humeri that were found in the clay matrix, portions of which have been lost. The articular head in the best-preserved specimen (Fig. 2, *E*) is oval in shape, and is not widely separated from the lateral process, which is much nearer the head than is usual in Permian reptiles. The bicipital fossa is rather shallow. The distal extremity is thin and flat, and is only moderately expanded on the ulnar side. The entepicondylar foramen is small, and is bridged over by a very delicate bar of bone, so delicate that it has been lost in all our specimens. Indeed, so thin is the broken edge left above the foramen that for a time I was in doubt as to whether it was not merely a notch. I am now convinced that the foramen was closed in; nevertheless it seems to be obsolescent. On the radial side there is an ectepicondylar foramen, quite as in modern lizards, formed by a slight bridge over the end of the ectepicondylar groove in the adult humerus, but wholly wanting in the juvenile specimens. The capitellum is well formed, as is also the

trochlear surface for the ulna. Both are small, but the joint here was evidently unusually compact and strong.

The planes of the two extremities of the humerus are turned nearly at right angles with one another. One would not recognize the figure given by Broom of the humerus of *Ophiodeirus* as that of an allied animal even, much less as that of *Araeoscelis*, were it not for the statement in the text that the two ends of the specimen, as figured, did not connect with each other. He thought that little was missing and figures the two ends in the same plane, though an examination of the humerus of *Araeoscelis*, as figured by me, should have convinced him of his error. As a matter of fact, taking as indices the two ends as figured, a slender cylindrical piece of the shaft 12 mm. in length was missing, giving a total length of about 50 mm. for the whole humerus, a trifle less than that of the adult humeri here figured. With these corrections his figured humerus may well be that of *Araeoscelis*.

There are no complete specimens of *radii* or *ulnae* preserved, though there are several partly complete. There can be scarcely a doubt that they were as long as the humerus. In two specimens the proximal ends are preserved in relation with the humerus, and two others have the distal ends preserved in relation with the carpus. Both bones are of equal size and are nearly straight. The radius has a cupped surface at the proximal end and a moderately expanded distal end. The ulna has a moderately produced olecranon; the distal end is a little less broad than that of the radius; there is no articular surface for a pisiform.

*Carpus* (Fig. 2, *F*).—The carpus and hand of *Araeoscelis* are so unlike those of other known contemporary reptiles that careful study was necessary for their interpretation. Fortunately, however, the material is good, and pretty nearly complete, consisting chiefly of two specimens, both with the carpals nearly all in position, together with the distal ends of the epipodials and the proximal ends of some of the metacarpals. The better of these specimens has the bones cemented together in a nodule that was inclosed in clay, which was cleanly washed away, leaving the bones visible. The wrist was compressed a little and flexed, so that the radius and ulna had slipped backward and downward, carrying the radiale

with them. Nor is there anything left in this specimen of the first and second metacarpals and the first carpale. The second specimen includes the epipodial and mesopodial bones and the proximal ends of the first and second metacarpals; the intermedium is not visible, possibly it is lost. There is also much more of the metapodials than in the other specimen, though none is complete. In a separate piece of clay at least three fingers were lying in position, but only the three metacarpals and some of their phalanges were preserved in place. These have been added to the figure made from the first specimen in dotted lines. The three specimens are the same or nearly the same size.

The *ulnare* is a stout, thick bone, which forms half of the articular surface for the ulna. It rests only slightly on the fifth carpale, though more than is shown in the figure, since it underlaps it to a small extent. At its lower, outer angle there is a small notch, all that seems to represent the perforating foramen. Its outer border is straight, and joins the inner border of the intermedium closely. The *intermedium* is a cuboid bone, a little wider below than above, with a considerable concave articular surface at each end, that of the proximal end continuing smoothly the ulnar articular surface. The *radiale* is seen only from the proximal side, as it lies back of the other carpal bones at the ends of the radius and ulna, the ulna partly rotated on its long axis. This surface shows an excavation where it partly covered the centrale. On the ulnar border there is a distinct notch between it and the intermedium that is puzzling. Lying by the side of the radiale there is a small nodular bone which must be either the first carpale or the first centrale; I have dotted it as the centrale. The *centrale* is a narrow bone with peculiar relations. At its inner side it articulates with the outer angle of the fifth carpale. The fifth carpale is also unlike that of any other Permian reptile that I know in its large size and relations with the fourth carpale, which it excludes from the proximal bones. The fourth carpale is small. It interlocks with both the centrale and the fifth carpale. The third carpale has a flat, rectangular anterior surface, a little longer than wide. It articulates above with the outer end of the centrale, and on each side with an adjacent carpale. The first carpale is a small bone.

The *fingers* are remarkable, so far as they are preserved. The great size of the ulnar ones over the radials suggested at first the possibility of error in their determination. As shown in the illustration, the unbroken lines represent bones of the more complete specimen, while those shown in dotted lines are taken from the other two specimens as they lie in place. There can be no legitimate doubt of the phalangeal formula, 2, 3, 4, 5, 3. Not a few slender phalanges are preserved loosely, belonging in the fingers. The claws are elongated and sharply pointed.

### PELVIC GIRDLE AND EXTREMITY

*Pelvis* (Fig. 4, *V*).—The more or less complete pelvis is preserved in three different specimens. In addition, there are two isolated ischia preserved in small nodules; one of these is of a young animal, the other of a nearly full-grown one, though a trifle smaller than the largest. These two small ischia have been used to complete the drawings made from an adult specimen. The pubes in the three associated skeletons shown in the figures are determinable in all details. The ilia are concealed in the pelves associated with the vertebrae, but there are two incomplete ones that were found free in the clay, in perfect preservation, save for the loss of the greater part of the posterior process.

The ilium, so far as it is determinable, shows no peculiarities of note to distinguish it from the common pelycosaur type, especially that of the poliosaurids. It has a rather slender posterior process, like that of *Varanosaurus*. Nor is the ischium at all peculiar; it is, indeed, of the form of all the ischia known of the American Permian, meeting its mate in a broad symphysis, and doubtless forming a more or less spout-shaped orifice to the pelvis. The pubis, however, departs markedly from the universal pelycosaur type, that observed in *Dimetrodon*, *Sphenacodon*, *Varanosaurus*, etc., agreeing rather better with that of *Casea*. In the fully adult specimens it meets the ischium in a nearly complete sutural union, leaving no puboischiadic vacuity, or a very small one, such as is always found in the true pelycosaurs. It is subquadrate in shape, with its superior outer margin somewhat thickened and emarginate, but not forming a spout-like anterior

projection. Broom compares the pelvis of *Ophiodeirus*, or his so-called *Bolosaurus*, with that of *Poecilospondylus*, but restores the latter wrongly. All the Poliosauridae, as indeed all of the Pelycosauria in the narrower sense, have a very characteristic pubis, standing horizontally far in advance of the true pelvic brim. I have seen the type specimen of *Poecilospondylus* and know that it is intimately allied to the genus I have described as *Varanosaurus*[1] but which is not congeneric with the genotype. Indeed, there is no more characteristic bone in the true Pelycosauria than the pubis, an element that I have relied upon, perhaps unduly, as a determinant of the relationships between the Sphenacodontidae and Poliosauridae.

Numerous juvenile or incomplete *femora* (Fig. 5, *A–D*) are represented among the free material found in the clay, but there is only one complete femur of an adult, with parts of three others. It is the longest bone in the skeleton, measuring about $2\frac{1}{2}$ inches in length. In front view the bone is nearly straight, with a long, cylindrical shaft and only moderately expanded extremities. In side view the bone is shaped much like the italic letter *f*, with the concavity above, the convexity below, on the front side. The head is stout and rounded, with its articular surface almost wholly at the extremity. The trochanter, a rather thin plate, springs inward and backward nearly at right angles, a little below the head, and continues as a thin edge, winding about the shaft till it reaches the middle, a little above the middle of the bone, and then continues as a linea aspera to the lower third, where it becomes obsolete. The tibial condyle juts inward, forming a right angle. The tibial surface is narrow, but connects broadly with the fibular surface. The two surfaces together make an angle of nearly 45 degrees with the long axis of the bone.

*Tibia and fibula.*—The tibia and fibula (Fig. 5, *E–I*), like the radius and ulna, are remarkably slender bones, fully as long as the femur. No free specimen of either bone is preserved entire, though one of each, in all probability those belonging with the femur

[1] The recent descriptions by Broili and Watson of the genotype of *Varanosaurus*, *V. acutirostris*, disclose, as I suspected, generic differences from the species *V. brevirostris* Williston. I therefore propose the generic name *Varanoops* for the latter.

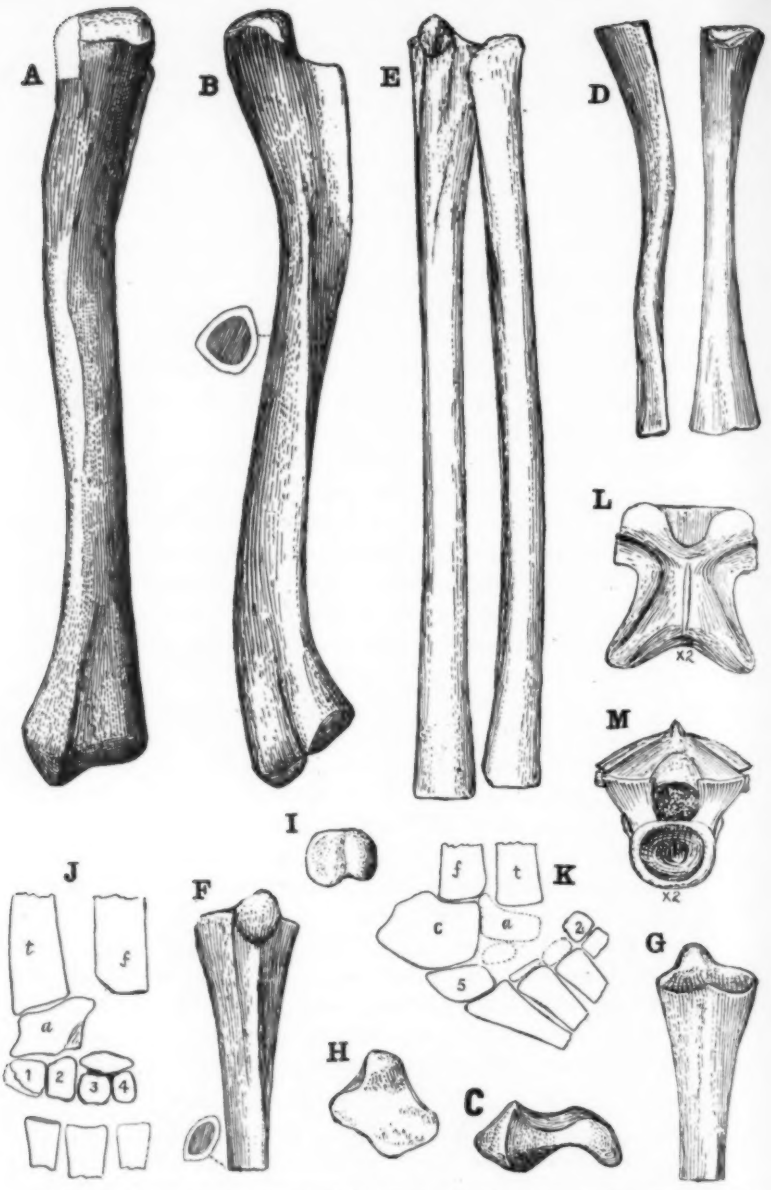


FIG. 5.—*Araeoscelis gracilis:* *A*, right femur, obliquely from above, adult; *B*, the same, obliquely from tibial side; *C*, distal end of same; *D*, femur of half-grown specimen, from side and front; E, tibia and fibula, adult, from the front; *F*, right tibia, proximal end, from the front, adult; *G*, the same, from behind; *H*, the same, from above; *I*, fibula, distal end; *J*, part of tarsus of Fig. 1, *B*; *K*, part of tarsus, immature; *L*, dorsal vertebra, from above; *M*, the same, from the front. All except *L* and *M* enlarged one-half.

that I have figured, are very nearly complete. In Fig. 5, *E*, the two bones are shown as completed from these and other specimens, aided by the complete specimens of a little smaller size shown in the associated skeleton of Figs. 1 and 2. The tibia (Fig. 5, *E–H*) is considerably expanded above, and has a prominent cnemial ridge ending in a rounded, rugose, cnemial crest above, for the attachment of what was evidently a strong quadriceps extensor ligament. Its upper surface is gently concave and fits very perfectly the distal articular surface of the femur. Its shaft is nearly straight and nearly cylindrical, or a little flattened. Its lower extremity is but little dilated, and its end is squarely truncate. The fibula is a little more curved, but scarcely differs in size from the tibia. Its upper end is moderately dilated on an oblique plane. Its lower extremity, as shown in Fig. 5, *A*, is nearly cylindrical, its articular surface distinctly divided into two facets, the one on the tibial side for articulation with the astragalus, a little narrower than the calcaneal, and rounded.

*Foot.*—The *tarsus* (Fig. 5, *J*, *K*), more or less complete, is preserved in two specimens, and in part in a third. Of one of these the bones are shown as they lie at the ends of the tibia and fibula in Fig. 5, *B*, and as brought as nearly as possible into their articular relations in Fig. 5, *J*. The tibia in this illustration is shown partly from the side and has apparently undergone a slight external curvature, though it is possible that this curvature is natural, and that I have represented the shaft in Fig. 5, *E*, too straight on the lower part. The astragalus is a small cuboid bone, very different in form from that of other known Permian reptiles, in that I can detect no surface on the inner side for the arthrodial articulation of the tibia. Its articulation with the tibia seems to have been firm and close, with not much motion. Lying at the outer side of this bone is a smaller one which can be interpreted only as a centrale of small size, articulating with the third and fourth tarsalia and probably somewhat with the astragalus. This is a rather unusual position for the centrale, but it seems certain that such were its relations. The first two tarsalia are relatively large, the third and fourth small. The fifth tarsale and the calcaneum are missing in this specimen.

A second specimen, in a small block of matrix belonging with a smaller animal, has the bones in the positions shown in Fig. 5, *K*. The distal ends of the epipodals, the calcaneum, fifth tarsale, and first tarsale are shown very clearly in the outline, but in their excavation from the hard matrix the surface of the tarsal bones has been somewhat injured. Crowded in the space below the tibia the bones of the external side of the tarsus are more confused and injured; but they confirm, so far as they can be deciphered, the arrangement shown in Fig. 5, *J*. The calcaneum (Fig. 4, *M*) is shown very perfectly and undistorted in a free specimen found in the clay. The heel is distinctly produced and has a slight cartilaginous thickening on its border for the Achilles tendon. The tibial surface shows very distinctly the notch for the perforating foramen. Elsewhere the borders are rather thin, save that for the articulation with the fibula. The fifth tarsale is shown very completely. It is of unusually large size, filling out the space between the calcaneum and the fifth metatarsal. All these bones in this specimen lie evidently in a natural position, the bones closely articulated.

Only four metatarsals are preserved together in any specimen, though the presence of the first tarsale would seem definitely to indicate the presence of the full five. It is also evident from these that the bones of the fibular side were stronger than those of the tibial, corresponding to those of the front feet, though the difference is not so great. Parts of three digits are shown in Fig. 4, *R*, as they were preserved in a small mass of clay. Doubtless the whole foot or the greater part of it had been present, but only these were recovered, though it is probable that the bones shown in Fig. 4, *S*, belong with the same specimen. The single metatarsal of adult size shown in Fig. 4, *U*, seems to correspond in its proximal and distal ends with the fourth; and it is evident that the digit showing the two phalanges of Fig. 4, *R*, is the fifth. The phalanges shown in Fig. 4, *S*, are in all probability the distal ones belonging with the two metatarsals shown in Fig. 4, *R*, that is, of the third and fourth digits, and that two proximal ones of each digit were ones probably corresponding in size pretty well with those of the fifth toe of Fig. 4, *R*. On these assumptions the feet may be restored with much probability.

## RELATIONSHIPS

*Araeoscelis* is the first paleozoic reptile in which a typical upper temporal vacuity has been definitely recognized. The Proganosauria, only, from an approximately equivalent age, have been accredited by Huene with a single, upper temporal vacuity, and doubtless correctly, but its boundaries and position have not yet been certainly determined. Inasmuch as great importance has been attributed to the number and boundaries of these openings in the relationships of reptiles, it will be well to discuss briefly all those forms in which only an upper opening is known or supposed to be present. Various theories have been proposed concerning their origin and relationships, but in my opinion they are as yet for the most part speculations, or at the most hypotheses. Attempts to base a primary classification of the order chiefly on the number of temporal openings so far have not been very successful. The most meritorious of these attempts is that of Professor Osborn, which, though it can no longer be accepted as the true solution of the reptilian phylogeny, did much to place the classification of reptiles on a more secure basis; notwithstanding its faults, its merits are obvious. All students of the order are in practical accord as regards the phyletic relationships of the double-arched forms. It is only concerning those groups in which there is but a single opening that grave doubt and uncertainty yet remain. The single vacuity, when present, is so inconstant in its position and in its boundaries that one is seldom certain whether it is the upper, or lower, either or both; or, indeed, as Watson thinks, in some cases neither!

The following groups of reptiles, more generally considered to be orders, have a single temporal vacuity on each side: Ichthyosauria, Sauropterygia, "Pelycosauria," Placodontia, Therapsida, Squamata and, if Huene is correct, the Proganosauria. Of these the Pelycosauria and Therapsida may at once be dismissed in any discussion of the relationships of *Araeoscelis*, since the opening, whether upper or lower or neither, has such different relations and boundaries as to preclude any immediate phyletic relationships. And, of the others, the Sauropterygia can have only a remote relationship and may be dismissed from the discussion. In addition

to these, some poorly known forms that have long been classed with the rhynchocephalian reptiles, under the assumption that any primitive reptile in which the temporal region was unknown probably was allied to *Sphenodon*, show such possible or probable resemblances to *Araeoscelis* as to merit consideration.

*Squamata.*—I have no hesitation in saying that the skull and skeleton of *Araeoscelis* present distinctively primitive characters of the *Squamata*, to such an extent indeed that I believe the genus has a definite phylogenetic relationship with the order. In fact, as far as the skull is concerned, all that seems necessary to convert *Araeoscelis* into a primitive lizard is the erosion of the lower part of the squamosal bone until only a slender rod is left along the under side of the postorbital, and the development of streptostyly in the quadrate, which would necessarily ensue with the loss of the support of the squamosal. The quadrate is supported quite as in the lizards by the tabulare and paroccipital, in conjunction with the squamosal. The quadrate itself retains some of its primitive characters in its moderately expanded upper end, which, however, is much less in extent than in other known contemporary reptiles. It is visible in part from the side, and fully so from behind. The postorbital is peculiar and unlike that of other known reptiles in that it takes no part in the formation of the posterior border of the orbit. In conjunction with the postfrontal it is quite like that of the mosasaurs and lizards in its extension backward nearly to the tabulare. Among mosasaurs I have seen indications of a sutural division of the "postfronto-orbital," and I have little doubt that the bone is really composed of the two elements. If it be really only a single bone, it must be the postorbital, not the postfrontal. In the reduction of the lacrimal to a small or vestigial bone we have another pronounced lacertilian character, never before observed in the earliest reptiles.

Unfortunately I have been unable to determine all the details of the palate. Although teeth are not known on the vomers[1] of

[1] For some years I was inclined to accept the conclusions of Broom that the so-called vomers of most reptiles were not homologous with the vomer of mammals, which represented the parasphenoid; and to adopt the name he proposed for them, prevomers. The more recent studies of Gaupp, Fuchs, Versluys, and Terry throw grave doubt, to say the least, over these conclusions. I therefore return to the use of the term "vomer."

squamate reptiles, their presence in *Araeoscelis* is only what would be expected in a primitive lizard. Nor is the presence of teeth on the transverse bone (if it be distinct) a character to which any weight can be attached. Though no lizards have such teeth we may be sure that their ancestors had them.

In the structure of the skeleton of *Araeoscelis* there is very little that would not confidently be expected in the primitive lizard. The ribs of the neck and lumbar region are single-headed in the strictest sense, not holocephalous, as in the cotylosaurs, and they articulate exclusively with the centrum. In the dorsal region they are dichocephalous, but the head and tubercle are close together, separated only by a short emargination. The head is articulated, unlike the condition in contemporary reptiles, high up on the side of the centrum near the front end, the tubercle to a short diapophysis on a level with and just back of the anterior zygapophyses. The fusion of these two articulations, or, what is more probable, a loss of the diapophysis, which actually occurs in the lumbar region, would make the rib attachment typically lacertilian. I am quite sure that the primitive lizards had dichocephalous or holocephalous ribs, that is, capitular and tubercular articulations. *Araeoscelis* offers a rational explanation of the way the very peculiar rib attachment of the Squamata arose.

The pectoral girdle shows certain peculiarities not known among the Squamata, especially the separate articular facets in front of the glenoid facet, and the possible absence of the supracoracoid foramen. The distinction of the coracoid is not quite certain, though the dotted line of the figure represents what seems to be a real sutural division. I have urged that the posterior coracoid bone has been lost in all modern reptiles; that such a bone was present in the ancestral lizard is quite certain.

In the anterior extremity the presence of a distinct ectepicondylar foramen, quite as in the lizards, is suggestive, at least, of genetic relationships; and there is also a suggestion that the entepicondylar foramen was obsolescent. The structure of the feet is unlike that of the contemporary reptiles in the elongated calcaneum and reduced astragalus. The pelvis is plate-like, without a decided pubo-ischiadic vacuity; but no other kind of a pelvis could be expected in the primitive lizards.

The elongation of the cervical vertebrae was clearly a specialization and not an ancestral character; but aside from this and the peculiar scapula, I can see nothing in the entire skeleton that might not have been confidently predicted in the ancestral lizard. It may be objected that the thecodont, or more properly protothecodont, teeth were an aberrant character; that the lizard ancestor must have had, like the living ones, acrodont or pleurodont teeth. On the contrary, I believe that the teeth primitively in the Squamata were protothecodont, which, by the loss of the parapet of bone on the inner side of the maxillae, and the anterior part of the coronoid, became pleurodont. Moreover, the teeth in the mosasaurs are attached in shallow cavities. In Fig. 3, *G*, I give a sketch drawing of the skull of *Opetiosaurus* Kramb., the earliest known skull of a squamate reptile, from the uppermost part of the Lower Cretaceous. The figure was made by me from the type specimen in the Munich museum, and differs somewhat from previous ones by Kramberger and Nopsca.

*Proterosaurus*.—There are certain marked resemblances between *Araeoscelis* and *Protorosaurus* which may, and probably do, indicate genetic relationships. Unfortunately much doubt remains as to the structure of the skull in this genus, notwithstanding the numerous specimens which have been studied during the past two centuries. Seeley's interpretation of the skull structure of *P. speneri* has been received with considerable doubt by later students. I have examined the specimen on which he based his results chiefly, preserved in the collection of the Royal College of Surgeons, but could make little of it; my examination, however, was brief, and without the aid of Seeley's paper. Nevertheless, I am inclined to the belief that his interpretation of the elements will eventually be found to be approximately correct. He figures the temporal region as open at the sides of the narrow parietals. If it should be found that the side was largely covered below by the squamosal, leaving a vacuity above, the structure would be essentially like that of *Araeoscelis*.

There is certainly as much justification for this hypothesis as there is for the one usually accepted, the presence of two temporal arches, for which I can see no evidence whatever. Nevertheless,

it was on this assumption and the equally unjustified assumption of a superior temporal vacuity in *Paleohatteria*, that these two genera and others even more indeterminate have been almost unreservedly classed either among the Rhynchocephalia or as a group of the Diaptosauria, of which the true Rhynchocephalia are another member. As I have elsewhere said, *Sphenodon* and the Rhynchocephalia have been, in the past, a cloak which has covered a multitude of taxonomic and phylogenetic sins. We have tried to trace all reptiles back to a primitive double-arched condition, on the assumption that *Sphenodon* is a very primitive reptile. It now seems more than probable that a single perforation of the temporal roof was the more primitive condition among reptiles, and that the Squamata are, in this respect, more primitive than the Rhynchocephalia. It has been assumed, indeed, that the Squamata themselves were derived from a primitive double-arched condition by the loss of the lower arcade, an assumption that in itself would seem to be improbable. Is it reasonable to suppose that the quadrate lost its fixity and became streptostylic suddenly, which would necessarily have been the case by the final loss of the quadratojugal arch? It would be far more reasonable to suppose that the gradual loss of a large squamosal, such as is found in *Araeoscelis*, permitted the gradual acquisition of streptostyly.

Seeley also figures a small antorbital vacuity in *Protorosaurus*, but with doubt; there is certainly none such in *Araeoscelis*. The lacrimal, according to Seeley, is small in *Protorosaurus*. So far, then, as I can see, there is nothing known in the skull of *Protorosaurus* that would prevent the immediate association of the genus with *Araeoscelis*.

In the skeletal structure *Protorosaurus* shows some remarkable resemblances to *Araeoscelis:* in the elongated cervical vertebrae, in the attachment of cervical and dorsal ribs, and in the general hollowness of the bones of the skeleton. These characters, in connection with the probable, or at least possible, resemblances of the skull, are, I believe, more than coincidences; they are genetic, not homoplastic.

Unfortunately little is known of the structure of the girdles in *Protorosaurus*. The vertebrae show distinct differences in the

elongation of the spines and in the reduced number of dorsals, though I think that the last-mentioned character is doubtful. The limb bones are not so much curved as in *Araeoscelis* but the epipodials are nearly as long as the propodials. Von Meyer also states that there are no epicondylar foramina in the humerus, and Seeley does not figure or mention any. The presence of a small ectepicondylar foramen, however, might easily have been overlooked, and I suspect that a close examination of adult specimens will disclose its presence. The bones are all very hollow as in *Araeoscelis*.

*Kadaliosaurus*.—There also seems to be much probability of a close genetic relationship between *Araeoscelis* and *Kadaliosaurus*, as shown in the skeletal bones in the absence of all knowledge of the skull. I had the pleasure of studying the type specimen of *Kadaliosaurus* the past year at Leipzig, thanks to the kindness of Drs. Stille and Krenkel. So far as the shapes of the limb bones and vertebrae are concerned, they seem almost identical with those of *Araeoscelis*. There is, I am convinced, an ectepicondylar foramen in the humerus, as Credner thought; there was probably also an entepicondylar foramen, though its existence cannot be proved, because of the loss of the ulnar border in the impression of the humerus, where the foramen should be. That the two genera are closely related I have little doubt, though it is hazardous to express a very decided conviction in the absence of any knowledge of the skull. *Kadaliosaurus*, however, differs generically in the structure of the long bones. I convinced myself thoroughly of the statement of Credner that the bones are not hollow, but are composed of cancellous tissue; the ribs, however, like those of *Araeoscelis*, are hollow. There is, also, a strong armature of ventral ribs, not the slightest indications of which have been observed in *Araeoscelis*. Further speculations as to the relationships of the two genera will be idle until the skull of *Kadaliosaurus* is discovered; the characters, so far as they are known, ally the two genera closely.

*Paleohatteria*.—This genus has long been associated with *Protorosaurus* as a member of the Protorosauria, or Rhynchocephalia, on the assumption of two temporal arches. We have seen how small was the justification for the assumption in *Protorosaurus*

and *Kadaliosaurus;* there is even less for *Paleohatteria*. We have tried to make every doubtful form in the past related to *Sphenodon;* even *Procolophon*, a true cotylosaur, has been placed in the same group, as a member of the Diaptosauria. As a matter of fact, *Paleohatteria* is not intimately related to the primitive rhynchocephalian stem, but is more closely allied to the so-called Pelycosauria, or even to the Proganosauria, as Baur first located it. I had the privilege, also, the past year, of studying the type specimens of *Paleohatteria* in Leipzig. Unfortunately some of the specimens had been loaned at the time of my visit to the museum, but the ones showing most conclusively the skull and skeletal structure were available. The results of my observations it will be worth while to reproduce here, though not immediately pertinent to the present subject. The skull, as shown in Credner's Plate XXIV, Fig. 3, is in my opinion preserved in a more natural profile than is any of the others, and is, I believe, more complete. The outline as I traced it is more complete and perfect than Credner figured it. The lower temporal opening is definitely shown, as are also the relations of the bone marked *sq* (quadratojugal?). Under the most careful scrutiny with a lens I could find no evidence of an upper vacuity. Neither do I believe that there is evidence of sclerotic plates in the orbits, though I did not see all the specimens.[1] The skull is rounded posteriorly, not projecting, as Jaekel has figured it. There is nothing in this specimen to suggest an upper temporal vacuity, nor could I find such evidences in any other specimen available for study. I could not distinguish the sutures between the prefrontal and lacrimal in any specimen; the lacrimal is certainly longer than Credner figured it, and it may have reached the nares. The upper surface of the skull, as stated by Credner, is distinctly rugose.

Credner's figures (Plate XXIV) of the scapula and coracoid are erroneous. The two are in close relation, but with the division visible (Fig. 6). The scapula seems to be somewhat longer than is visible, the upper end hidden below the humerus. The lower

[1] It has generally been assumed that the presence of sclerotic plates means aquatic habits, the fact being overlooked that there are not a few purely terrestrial lizards in which the sclerals are highly developed.

end is expanded, as in the allied American reptiles. The coracoid lies over the stem of the clavicle, and in all probability is composed of the anterior element only, which is the case with the numerous known scapulae coracoids of *Varanoops brevirostris*. The clavicle was represented by Credner as a slender rod, without designation; its shape is like that of *Ophiacodon*, and it lies in articulation with the interclavicle and the upper front margin of the scapula. I thought that I recognized the usual supracoracoid foramen in the impression of the coracoid, but in this I may have been mistaken. The outline of the coracoid is clearly shown on both sides of this specimen. The outline of the front border of the scapula is also clearly apparent, broadly convex below, gently emarginate above. In fact, the structure throughout of the pectoral girdle is like that of *Varanoops brevirostris*, or as it would be in an immature specimen of that species. The ribs are holocephalous, like those of *Ophiacodon*. The humerus in this specimen is turned outward, not inward, and only an entepicondylar foramen is present. There are not more than three pairs of sacral ribs. In much probability the number of presacral vertebrae is twenty-seven, the constant number in the Pelycosauria in the more restricted sense. In brief, *Paleohatteria* is in every respect a member of the Pelycosauria (*sensu latiore*), of which it represents a family, Paleohatteriidae (Baur), of co-ordinate value with the Poliosauridae or Sphenacodontidae.

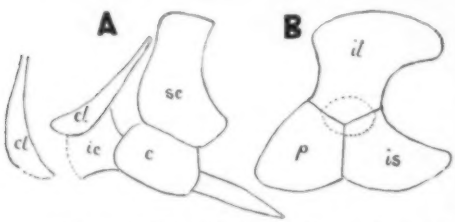


FIG. 6.—*Paleohatteria longicaudata* Credner: *A*, pectoral girdle, in part; *B*, left pelvic bones: *sc*, scapula; *c*, coracoid; *ic*, interclavicle; *cl*, clavicle; *il*, ilium; *is*, ischium; *p*, pubis.

*Pleurosaurus* (*Acrosaurus*).—This genus has generally been classed with the Rhynchocephalia in the narrow sense, notwithstanding the fact that it has but a single temporal opening, a fact that has previously been known and definitely confirmed by Watson. I had the pleasure of studying the excellent material of this genus preserved in the Munich museum, for which my thanks

are due to Dr. Broili. I reached the decided conviction that *Acrosaurus* is merely the young of *Pleurosaurus*. Of course the presence of a single upper temporal vacuity excludes the form decisively and absolutely from the Rhynchocephalia or Diaptosauria, even. Whether or not it is intimately allied to *Araeoscelis* and *Protorosaurus* I shall not presume to say; but certainly its claims to such relations are vastly greater than those with the rhynchocephalian forms.

*Proganosauria.*—If Huene is correct in the attribution of a single upper temporal vacuity to *Mesosaurus* (and I believe that he is, notwithstanding the imperfect material that is in the collections of the skull of this genus), there may arise a question of the relationships between it and some of the forms I have briefly discussed. So far as the skeleton of the proganosaurs is concerned, it is simply an aquatic modification of the primitive cotylosaurian, or better, pelycosaurian type. Here, also, until the more precise structure of the skull is known, speculation is idle. The order Proganosauria may be accepted until it is proved that it has no claim for independent existence.

*Ichthyosauria.*—The origin and relationships of the Ichthyosauria have long been an unsolved problem, but little nearer solution today than it was a score of years ago, notwithstanding the brilliant discoveries of Dr. Merriam. On the strength of its generalized characters it has been associated with the rhynchocephalian type, as a member of the double-arched division of reptiles, under the hypothesis that the lower vacuity was secondarily closed by the encroachment of the orbit. More recently Huene has urged that its relationships are nearest with the Proganosauria, and with much reason. This much can be said: If all the known reptiles having a distinctive upper temporal opening have arisen from a single ancestral type, that is, are monophyletic, then the ichthyosaurs must be more closely related to the Squamata, *Protorosaurus*, and Proganosauria, than to any other known reptiles This much I believe: The Ichthyosauria are of very primitive origin; they have never possessed a lower temporal vacuity; the two bones of the temporal region, variously known as supratemporal and squamosal, point to a direct origin from the stego-

crotaphous reptiles, provided these bones are not both identical with those I call the tabulare and squamosal in the lacertilians and *Araeoscelis*. If they are identical, then the two phyla may have originated together.

The problem remains, What shall be done with *Araeoscelis?* To throw it into a common receptacle with *Dimetrodon*, *Edaphosaurus*, and *Casea* may be an easy way to dispose of the genus, but it is hardly scientific. Some classification, even the most conservative, it must have; and while I am vigorously opposed to the still more reprehensible practice of giving every form that is hard to understand a new group name, it is evident that to place *Araeoscelis* with the Pelycosauria is to increase the confusion.

I have urged that the resemblances of *Araeoscelis* to the Squamata would justify its inclusion in that order as a suborder, under the name Araeoscelidia, co-ordinate with the Lacertilia and the Ophidia. And I believe that will be its final disposition under some subordinal designation. But it seems to me that the relations with *Protorosaurus* and *Kadaliosaurus* are too definite, too pronounced, to warrant their dissociation. I would therefore propose to unite these three genera, together with, provisionally, *Haptodus* and *Callibrachion*, under the order Protorosauria of Seeley, and place the order immediately before the Squamata in any serial classification of reptiles.

## RESTORATION

The restoration of the skeleton shown in Fig. 7 is based upon the material described in the foregoing pages. I have omitted the tail because, while there are a sufficient number of caudal vertebrae preserved to show conclusively that it was long and slender, there are not enough preserved in connection to determine its length. I have little doubt that the number of vertebrae exceeded sixty. The precise lengths of the digits are also in a measure conjectural, since in no specimen is a digit preserved complete. Sufficient phalanges, however, have been recovered to enable one to reconstruct the fingers and toes with little chance of error, following the arrangement determined in other contemporary reptiles. The first digit of the hand is purely conjectural. It must have been

small, and may have been absent; the hand upon the whole seems to have been much like that of *Varanosaurus brevirostris*. The lengths of the anterior ribs are determined from one specimen in which they are preserved nearly completely in relation with the vertebrae. The lengths of the posterior ribs are conjectural. It is also assumed that there are not more than seven cervical vertebrae; there is a strong possibility, however, that the neck was longer.

In the life restoration (Fig. 8) I have added the tail in like proportion to that of slender living lizards. That it was as long as the head, neck, and trunk together there can be scarcely a doubt, for it is not often shorter in swift-crawling reptiles; it may have been longer. In much probability the living animal was covered with corneous scales; one can hardly conceive of a reptile with habits such as *Araeoscelis* must have had as having a bare skin, and it is quite certain that the body was not protected with bony scutes.

FIG. 7.—*Araeoscelis gracilis* Williston: Restoration of skeleton, about one-fourth natural size.

HABITS

Just what is the significance of some of the peculiar characters possessed by *Araeoscelis* I am at a loss to conjecture. That the creature was a swift-moving, crawling reptile there can be no doubt. That it was arboricolous I also believe; the pointed and curved ungual phalanges determine the presence of sharp claws in the living animal. The unusual development of the calcaneum and outer toes seems to indicate springing habits, and the curved femora and elongated epipodials resemble those of *Scleromochlus*, of whose leaping powers

there can be little doubt. The extremely hollow bones also suggest arboricolous habits. Why the creature had such elongated cervicals I do not see. At one time the idea was entertained that *Araeoscelis* possessed more or less of a *Flughaut*, because of the development of the outer fingers and the possible loss of

FIG. 8.—*Araeoscelis gracilis* Williston: Life restoration, about one-fourth natural size.

the first. And the cervical vertebrae certainly suggest those of the pterodactyls or birds, as Seeley has suggested of *Protorosaurus*. The presence of similar cervical vertebrae and hollow bones suggests somewhat similar habits for both these reptiles, but the vertebrae of *Protorosaurus* are clearly more like those of the crawling lizards, while those of *Araeoscelis* resemble more those

of snakes. The hind legs of *Protorosaurus* are longer than the front ones, and this is the case also with *Araeoscelis*, though not to the same extent. One can say with assurance that *Araeoscelis* was an extremely light and slender, terrestrial and arboreal reptile, with springing powers, and possibly with a parachute development of the body membrane. Its length, when adult, was about 2 feet.

## THE SKULL OF *CASEA*[1]

A preliminary description of the skull of *Casea*, as based on a single, not quite complete, specimen, has been given by me in my *American Permian Vertebrates*, with a promise of a further discussion whenever the additional material of the University collections should be worked out. One other skull has, so far, been discovered and prepared, though there is still a probability of others turning up in the future. This skull, unfortunately, had been somewhat injured in the collection of the material by the loss of much of the upper part in front of the parietal foramen. The right orbit is nearly complete and the lower part of the left, as also the lower part of the nares. The quadrates are somewhat displaced, but otherwise the skull is more perfect than the one previously described. The specimen is a part of a nearly complete skeleton which has not yet been worked out of its nodular matrix; it is of precisely the same size as the skeleton previously described. The premaxillae are complete, or nearly complete, and are in position with respect to each other and the maxillae. They project farther forward than did the incomplete ones of the previous specimen, terminating above in slender processes, which separate the nares narrowly. In the first-described specimen the nares had been somewhat injured, with the roof depressed, especially on the right side. The present specimen gives the lower side complete and quite undistorted, enabling me to restore the orifice with the aid of the other specimen, accurately, I think. It is possible that the orifice may have been a little higher than I have figured it (Figs. 9, 10). The nares, it is seen, are of enormous size, communicating immediately with the very large internal openings below

[1] Williston, *Jour. Geol.*, XVIII (1910); *American Permian Vertebrates* (1911).

them. Lying just within the orifice there is a thin, plate-like bone, evidently forming a turbinated structure, the sphenomaxillary.

Not much can be added to my description of the temporal vacuity. On the right side the orbital bar and inferior arcade are nearly complete, but on the left side they have been injured by the displacement of the quadrate. I think, however, as I suspected, that the vacuity is a little smaller than I figured it. Nothing definite can be said as to the presence of a distinct quadratojugal bone.

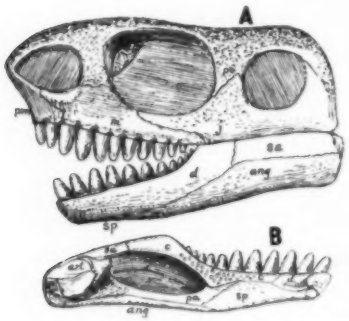


FIG. 9.—*Casea broilii* Williston: *A*, skull from the side; *B*, left mandible of same, from inner side, three-fifths natural size; *pm*, premaxilla; *m*, maxilla; *po*, postorbital; *j*, jugal; *d*, dentary; *sa*, surangular; *ang*, angular; *sp*, splenial; *art*, articular; *pa*, prearticular; *c*, coronoid.

The palate, fortunately, is in such preservation that its structure, save in details, is very clear. The whole surface is closed, as in *Pantylus*, and is covered with small, but pointed, conical teeth. Large orifices in front, corresponding with those shown in the former figure, are the nares, situated immediately below the external openings. The two sides of the palate show divisions so alike that one cannot resist the conviction that some of them, at least, are sutural separations. Especially do the divisions running backward from the nares, which are not only alike on the two sides, but which agree with those of the former skull, indicate the sutures between palatines and pterygoids. One cannot be sure of the division between the pterygoids and vomers, covered, as the surface is, with numerous small teeth, which cannot be entirely freed from the matrix; but a symmetrical depression on the two sides seems to indicate the sutures, as shown by dotted lines in the figure. On either side behind, there are two divisions, which seem to be exactly alike on the two sides, one running forward and outward from the inner extremity of what would be the transverse bones if present; the other forward and inward to near the front end

of the interpterygoidal space. That all of these should be fractures, so exactly alike on the two sides, seems strange, but there can hardly be any other interpretation of the inner divisions, at least. They all bear teeth forming a continuous dentigerous surface between the mandibles, back of the nares. The two inner pieces are crowded nearly in contact over what is probably a slender parasphenoid in this specimen; in the other specimen, however, the base of a narrow parasphenoid is seen between the two sides.

In one or the other of the two skulls the structure of the posterior palatine region is definitely shown. The basisphenoid is a broad, flat, or gently concave bone, lying contiguous with the posterior processes of the pterygoids in front, and terminating in front, as I have figured it, apparently in a slender parasphenoid. Posteriorly the very stout stapes fits closely into an interval between the posterior angle of the basisphenoid and the exoccipitals. It is directed outward and backward, as a heavy, somewhat curved, cylindrical rod, to near the lower end of the quadrate, lying in close relation to the posterior process of the pterygoid.

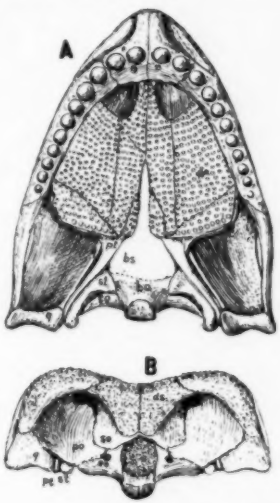


FIG. 10.—*Casea broilii*: *A*, skull from below; *B*, the same, from behind, three-fifths natural size; *po*, paroccipital; *pa*, palatine; *bs*, basisphenoid; *bo*, basioccipital; *pt*, pterygoid; *q*, quadrate; *st*, stapes; *eo*, exocciptal; *so*, supraoccipital *ds*, dermosupraoccipital.

The basioccipital forms the whole of the gently curved, cordate-shaped condyle, with a short, broad surface below in front. On either side the exoccipital is distinctly separated from the basioccipital, extending up on either side of the foramen magnum to near the top, as in *Dimetrodon*. These sutures are clearly shown; that between the exoccipital and paroccipital is less certain, though, from the agreement of lines on both sides in both specimens, I believe that the suture is situated as I have figured it in dotted lines. A small foramen for the posterior cranial nerves is visible as I

have figured it. The broad, outer concave surface of the occiput is formed chiefly by the paroccipital—I can detect nothing of the petrosal—leaving a small post-temporal vacuity above as an emargination of the upper side of the bone. At what seems evidently the junction of the paroccipital and supraoccipital there is a distinct notch, from which what seems to be a sutural line passes downward to join the exoccipital suture. The supraoccipitals form together a plate, somewhat convex in the middle above the foramen magnum, which extends upward to the under side of the parietals, as in lizards, but are covered, for the most part, by the loosely applied bones of the cranial roof, which descend to, or nearly to, the upper margin of the foramen magnum, with a slight notch in the middle. In one specimen they come quite to the margin, in the other they terminate some little distance above, owing to the greater depression of the skull roof in the former. These bones are rugose on the upper surface, forming a continuation of the cranial table. I suppose that they are the dermosupraoccipitals, joining the true supraoccipitals quite as in the cotylosaur *Labidosaurus;* but no certain line of distinction can be seen above. On the sides in each specimen a sutural line seems distinct, separating the bones from the lateral element, whatever it may be, of the suspensorial arch. As these lines agree in the two specimens, there would seem to be little doubt of their sutural character.

I cannot be sure of the structure of the process that curves downward on either side behind to cover the upper end of the quadrate. Since they join broadly the outer end of the paroccipitals behind, one would expect to find a distinct tabulare here; but if so, it cannot be demonstrated from these specimens.

With the exception of the loosely applied dermosupraoccipitals it will be seen that the whole structure of the occipital region, as I interpret it, resembles that of *Varanus*, except that the post-temporal vacuity is smaller, and that the exoccipitals take no part in the formation of the occipital condyle.

The sutures of the mandible are shown very satisfactorily in the two specimens, and doubtless I should have detected them in my previous study of them, had I then known what to expect.

The coronoid reaches posteriorly on the upper side of the meckelian orifice nearly to the anterior extremity of the articular; anteriorly this bone borders the alveolar margin as far forward as the third tooth. It is covered, for the most part, with small, conical teeth, like those of the opposite palatal surface. These teeth had been smoothly removed with the investing matrix in the first specimen described, but their attachments are clearly visible under a hand-lens; they are visible in the investing matrix of the second skull. The splenial enters into the mandibular symphysis below, as usual among the early vertebrates. The boundaries of the pre-articular are less distinct posteriorly, though certain evidences of sutural lines are visible as I have figured them.

The teeth in the second specimen are somewhat better preserved than in the first; they are of somewhat larger size, but their number and characters are quite the same.

Any comparison of the skull of *Casea* with that of other reptiles will be more or less speculative. It shares with *Diadectes*, *Pantylus*, and *Edaphosaurus* the short, broad skull and more or less elevated narial region. In all these the palatal region is practically closed in front and covered with more or less thickly set teeth, indicating similar food habits. From the nature of the obtuse mandibular and maxillary teeth, I had inferred herbivorous habits; but it is quite possible that the food may have consisted chiefly of the softer invertebrates. Against this assumption, however, is the very large abdominal capacity that suggests plant food. The skull, as I have before suggested, has a strange resemblance to that of *Amblyrhynchus*, the subaquatic Galapagos lizard, in the great development of the narial region.

The single large temporal vacuity reminds one of *Edaphosaurus*, but the intimate resemblances end there. Nor is there a very intimate relationship between *Casea*, the poliosaurids, as represented by *Varanoops*, or the ophiacodontids as represented by *Theropleura* or *Ophiacodon*. That the genus represents a distinct family there can be no doubt; its higher relationships must await further discoveries—I have little faith in phylogenetic speculations based on our present ignorance of the early reptilian faunas.

## ARRIBASAURUS, A NEW GENUS OF THEROMORPH REPTILES FROM NEW MEXICO

Among the collections made by Mr. David Baldwin for Professor Marsh more than thirty years ago, there is a considerable quantity of more or less broken and fragmentary bones of a small reptile from El Cobre Cañon, New Mexico. All of this material, or at least the greater part of it, was evidently collected from the surface at one spot where it had been washed from some bone-bed. The material consists, apparently, of the remains of a single species, represented by the bones of adults and young. Among the collections made by the University of Chicago expedition to the same region in the summer of 1911, there are a number of bones and fragments of bones collected from the surface near the west part of the same cañon, that evidently are of the same species as some if not all the remains of the Yale collection, if not also of the American Museum collection made by Baldwin for Professor Cope from El Cobre, which includes the type of the species *Dimetrodon navajoicus* Case. I should feel quite confident that the Chicago collection came from the same bone-bed deposit as the remains preserved at Yale University, were it not that the bones all seem to belong to a single individual, save for a small femur of a yet unnamed cotylosaur of very small size. Of the Yale material the larger part consists of the remains of immature animals, as shown by their smaller size and incomplete ossification of the ends of the long bones. There are, however, portions of the skeletons of at least two adults among the collection. The lower end of one of these adult specimens agrees so well with the humerus figured and described by Case under the name *Dimetrodon navajoicus*, that I feel fairly confident of their specific identity, notwithstanding the apparent absence of an ectepicondylar process in the specimen as figured by Case. That all this material at Yale and at Chicago belongs in a single genus there can be no reasonable doubt. If the adult specimens are later shown to belong to a distinct species it will be time enough to give a new name when the facts are known. The genus may therefore be defined as follows:

*Arribasaurus*, genus new. Teeth slender, conical, more elongate anteriorly, short and closely placed posteriorly. Spines of verte-

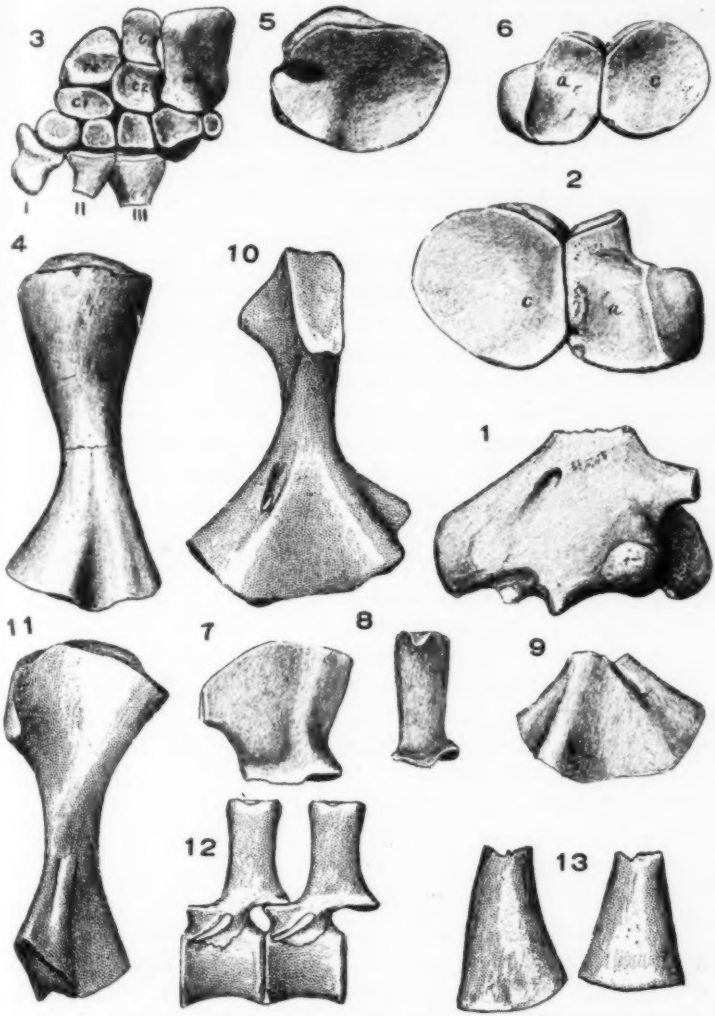


FIG. 11.—*Arribasaurus navajoicus* Case: *1*, distal end of left humerus, ventral side; *2*, calcaneum and astragalus, from the front; *3*, left carpus, from the front; *4*, left femur, dorsal side; *5*, pubis; *6*, right calcaneum and astragalus of young, from the front; *7*, spine of axis; *8*, spine of dorsal vertebra; *9*, distal end of young humerus; *10*, right immature humerus, dorsal side; *11*, the same, ulnar side; *12*, two dorsal vertebrae, from the side; *13*, distal end of tibia; *14*, distal end of fibula. All natural size.

brae (Fig. 11, *8*, *12*) short and flattened, with the upper extremity flattened ovate in section; axis with a broad spine, as in the Poliosauridae; diapophyses with a continuous articular surface, directed downward and forward, showing holocephalous ribs, as in *Ophiacodon*. Humerus (Fig. 11, *1*, *10*, *11*) with the lateral process high up on the shaft; distal extremity much expanded, its plane nearly at a right angle with that of the proximal end; carpus (Fig. 11, 3) very much as in *Ophiacodon;* the first centrale and inner carpalia larger. Pubis (Fig. 11, *5*) subcircular or subquadrate in outline, with the obturator foramen more or less notched (in the young at least); ischium and proximal tarsal bones (Fig. 11, *2*, *6*) as in *Ophiacodon;* femur with a rather slender shaft (Fig. 11, *4*). Length of animal probably about 5 feet.

So far as the skeletal bones and teeth are concerned, the genus seems to be related to *Ophiacodon*, but the pubis shows very distinctive characters, and the spines of the vertebrae are relatively much shorter; the humerus is also much more elongated. On the strength of the pubis alone, a very characteristic bone in the Pelycosauria, the genus is, I think, eliminated from the Poliosauridae or Ophiacodontidae; and the teeth will exclude it from the Sphenacodontidae. The pubis has a distinct resemblance to one which I figured erroneously as a calcaneum in my *American Permian Vertebrates* (Plate XXXI, Fig. 10, and Plate XXXII, Fig. 11), from the Craddock bone-bed, Texas; and it is possible that the femur, also figured in this work on Plate XXX, Fig. 4, may belong with this pubis, a yet unnamed genus, that may prove to be related to the present one.

## THE PRIMITIVE STRUCTURE OF THE MANDIBLE IN REPTILES AND AMPHIBIANS

Until within recent years the mandible of reptiles was thought to be composed of not more than six bones, originally named by Cuvier and Owen the articular, angular, surangular, coronoid, splenial, and dentary. In *Sphenodon* only was it known that one of these bones, the splenial, was absent. The bone long known as the splenial in the turtles occupies an anomalous position for that bone, overlying the inner side of the articular and remote

from the position of the splenial in other reptiles. Baur,[1] in 1895, discovered in the extinct *Toxochelys* a bone that corresponds to the true splenial of other reptiles, and recognized for the first time that the so-called splenial of other turtles really is homologous with a dermal element which is either wholly wanting or is indistinguishably fused with the articular in all other reptiles then known. Unfortunately, assuming that the bone so called in the Chelonia was the true splenial, he changed the names of the elements in other reptiles to correspond, naming that originally called the splenial by Owen the presplenial, causing thereby much confusion in nomenclature. In 1903 I recognized[2] for the first time in an another reptile this dermogenous element, in the plesiosaurs, and corrected Baur's error by naming it the prearticular, retaining the names of all the other elements as originally applied by Cuvier and Owen. Soon afterward Case recognized the prearticular in the Pelycosauria, and Branson in the Stegocephalia. Since then the name has come into general use, though other names were later proposed for the same bone (dermarticular Kingsley, goniale Gaupp). Five years ago I expressed the conviction that a separate prearticular would be found characteristic of all early reptiles; we now know that to be the fact. Typically the bone overlies the inner side of the articular, forming the inner margin of the suprameckelian orifice, and the posterior and superior margin of the posterior inframeckelian foramen, when it is present, its anterior end intercalated between the splenial and the coronoid. In other words, it has precisely the same relations as has the anterior inner part of the angular in the crocodiles (Fig. 12), in which no evidence has so far been adduced of a prearticular ossification. One wonders whether embryological investigation may not show a fused condition of prearticular and angular in these reptiles; in which case the so-called angular would properly be called the angular-prearticular, just as the so-called articular of lizards is really the articular-prearticular.

In all later reptiles the coronoid is a small element occupying the eminence of the mandible back of the teeth, articulating with

[1] Baur, *Anat. Anzeiger* (1895), p. 412.

[2] Williston. *Field Columb. Mus. Publ.*, No. 73, p. 30.

the dentary, surangular, and prearticular or angular, and also the splenial when present. It never extends farther forward than the posterior part of the dental series. In the same plesiosaurian mandible in which I recognized a separate prearticular, there was "a long, slender, flattened, trihedral bone, extending far forward along the alveolar margin, meeting its mate in the median symphysis" (Fig. 16), which I was forced to call the coronoid, though it was utterly unlike anything that had previously been recognized as the coronoid. Only within recent years has this peculiar structure of the coronoid been recognized in other plesiosaurs, by Andrews and Linder; doubtless it is characteristic of the order, testifying to its primitive origin. This elongate form of the coronoid is now known to be characteristic of all primitive reptiles. In these reptiles it lies along the inner alveolar margin of the mandible, extending toward the symphysis, but entering into union with its mate only in those reptiles having a long mandibular symphysis. Its posterior end occupies the position of the coronoid of later reptiles, that is, articulating with the anterior superior part of the surangular, chiefly on the inner side of the mandible, and forming the anterior margin of the meckelian orifice. It articulates with the prearticular below; it is always narrow.

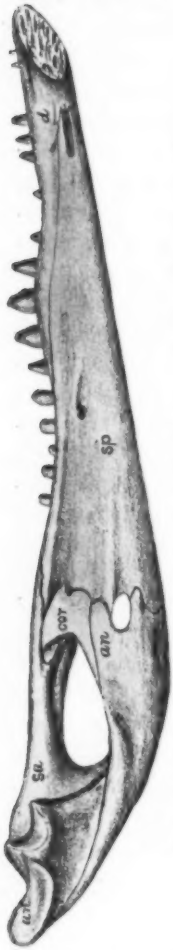


FIG. 12.—*Alligator mississippiensis:* Left mandible, inner side. Explanations as in Fig. 13.

The splenial in all modern reptiles, when present, is a thin bone covering more or less the inner side of the mandible anteriorly and the meckelian groove, extending rarely as far forward as the symphysis; it is not visible on the outer side of the mandible, or, if so, only to a very slight extent. As I stated some years ago,[1] "in all or nearly all reptiles having a greatly elongated

[1] Williston, *Jour. Geol.*, XVI (1906), 6.

mandibular symphysis, the splenial takes part in its union." But, this symphyseal union of the splenials in such forms is doubtless due to the recession of the symphysis, rather than to the retention of a primitive character, since in the alligator and crocodile, with a short symphysis, the splenials do not meet, while in the gavial, with a long symphysis, they do.

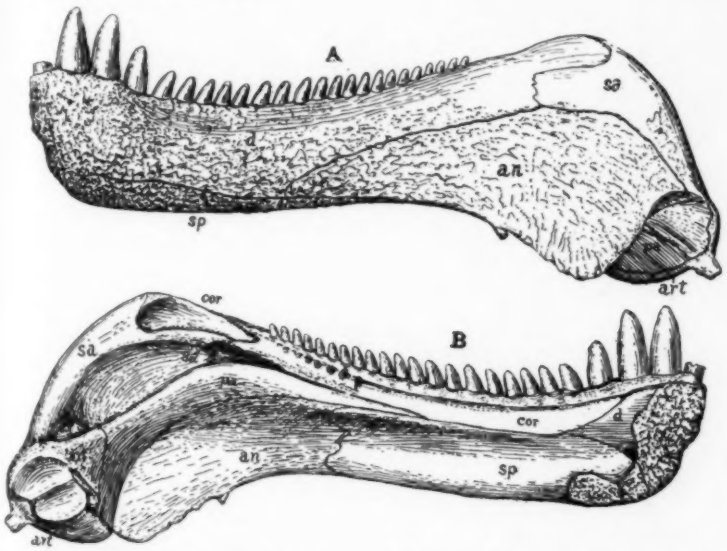


FIG. 13.—*Dimetrodon incisivus* Cope: *A*, left mandible, outer side; *B*, inner side of same; *cor*, coronoid; *d*, dentary; *sa*, surangular; *an*, angular; *art*, articular; *pa*, prearticular; *sp*, splenial.

Not only is the symphyseal union of the splenials a primitive character, as was first stated by me in 1911[1] and reaffirmed the following year, but, unlike modern reptiles, it enters more or less into the outer surface of the mandible, as I have figured it in various cotylosaurs (*Limnoscelis*, *Labidosaurus*, *Captorhinus*). These primitive characters may be summarized as follows:

The primitive mandible of reptiles is composed of seven distinct bones, the articular, prearticular, angular, surangular, coronoid, splenial, and dentary. The coronoid is elongated, extending along

[1] Williston, *American Permian Vertebrates*, p. 30.

the alveolar margin of the teeth toward the symphysis, and often bearing teeth. The prearticular forms the inner border of the meckelian orifice and is intercalated between the coronoid and splenial anteriorly. The splenial takes part in the mandibular symphysis, and is more or less visible on the outer side of the

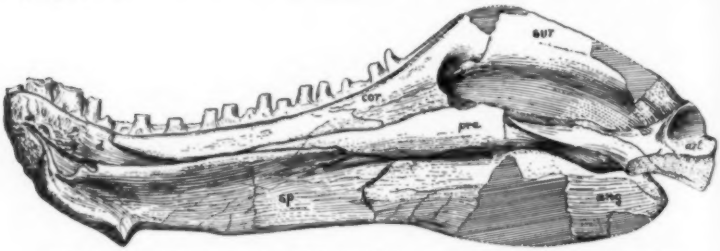


FIG. 14.—*Dimetrodon*, sp.: Right mandible, from inner side. Explanations as in Fig. 13.

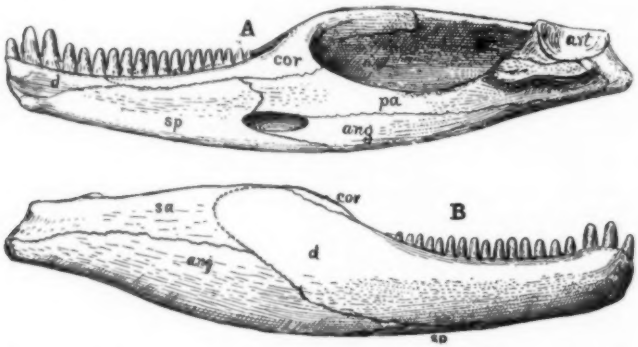


FIG. 15.—*Labidosaurus hamatus* Cope: *A*, right mandible, inner side; *B*, the same, outer side. Explanations as in Fig. 13.

mandible. A posterior inframeckelian foramen is present in the most primitive reptiles.

These characters I have determined in six different genera of Permian reptiles, and I doubt not that they will be found in all, from the Lower Permian at least. Figures of the mandibles of four of these are given herewith, and do not need detailed description (*Dimetrodon*, Figs. 13, 14; *Casea*, Fig. 9; *Labidosaurus*,

Fig. 15; and *Captorhinus*, Fig. 16). Photographic copies of the mandible of *Dimetrodon*, precisely as here figured (Fig. 13), were distributed to some of my correspondents in August of 1913. I was not then confident of the continuity of the coronoid bone throughout, and so briefly described it in *Science* of October 10, 1913, as possibly, though not probably, composed of two bones, the anterior one of which I called the alveolar. Later material satisfied me that there is but a single bone. Dr. Broom[1] refers to this description as of a distinct alveolar bone; doubtless it was an oversight, since he received a copy of Fig. 13 in August, as also my figures of the mandibles of *Trimerorhachis* and *Labidosaurus*, before he wrote his paper.

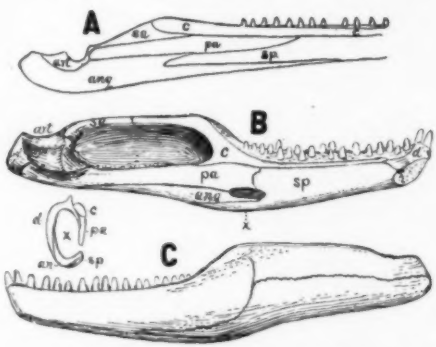


FIG. 16.—*Trinacromerum osborni* Williston: Left mandible to symphysis, inner side, after Williston, 1903; *B*, *Captorhinus aguti* Cope, left mandible, from within; *C*, the same, outer side. Explanations as in Fig. 13.

Since the foregoing went to the printer I have received from Dr. Broom another paper, published February 24, 1914, containing a description and figure of a mandible of a pelycosaur preserved in the National Museum, which he doubtfully referred to either *Dimetrodon* or "*Naosaurus*" (*Edaphosaurus*)! The only addition this paper makes to our knowledge is the precise connection between the coronoid and prearticular. He determines, however, without hesitation or doubt a suture separating the coronoid into two bones, the anterior of which he calls the precoronoid. At my request, Mr. Gilmore kindly sent me the specimen upon which Broom's studies were based. It is very clearly a species of *Dimetrodon*. I give herewith a more accurate figure of the specimen (Fig. 14). All the sutures, aside from the one in question, are

[1] Broom, *Bull. Amer. Mus. Nat. Hist.* (November, 1913).

clearly shown, especially in connection with my previous figure which Dr. Broom had at the time of his studies. That there is a real suture dividing the coronoid is not impossible, but there is nothing in the specimen to prove that it is not a crack, and not until it is corroborated by additional material should his figure be accepted as certain. Dr. Broom has made mistakes before in his hasty identification of cracks as sutures, and this may be another one. Dr. Broom states that he has "recently" seen a copy of my figure of the *Dimetrodon* jaw as here given (Fig. 13). "Recently" is evidently here used in a relative sense, since he

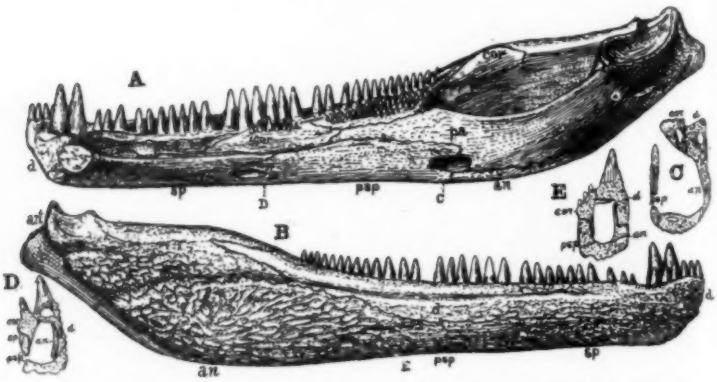


FIG. 17.—*Trimerorhachis alleni* Case: *A*, right mandible, inner side; *B*, the same, outer side; *C*, *D*, *E*, sections of mandible as designated; *psp*, postsplenial; *cor*, coronoid; *icor*, intercoronoid; *pcor*, precoronoid. Other explanations as in Fig. 13.

first saw the figure before he began his study of the American mandibles, in August, more than three months before he studied the specimen in the National Museum.

## AMPHIBIANS

In the structure of the mandible the amphibians are remarkably intermediate between the early reptiles and the contemporary crossopterygian fishes, differing from the latter chiefly in the reduced number of coronoids, and from the former chiefly in the possession of two additional coronoids and a splenial.

Until very recently our knowledge of the stegocephalian mandibular structure has been imperfect and more or less erroneous. Branson for the first time recognized in an amphibian the presence of a distinct prearticular, and correctly homologized what is now

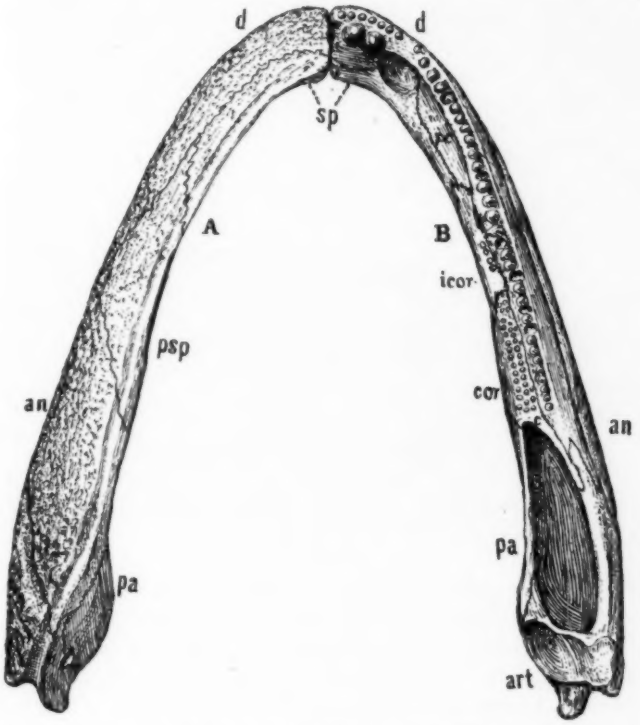


FIG. 18.—*Trimerorhachis insignis; A*, right mandible, from below; *B*, the same, from above. Explanations as in Figs. 13 and 17.

known as the true splenial with the infradentary of fishes. He erred in uniting the postsplenial with the angular, and in calling the intercoronoid and precoronoid the splenial. He also identified the true coronoid correctly. Watson very recently correctly homologized the true splenial with the infradentary of Branson,

and correctly identified the anterior coronoid. He erred in distinguishing the limits of the prearticular and in giving to the true coronoid the name epicoronoid as an element peculiar to amphibians.

The posterior splenial (Fig. 17, *psp*) was, I believe, for the first time recognized in any amphibian by me in the early part of last August, and its discovery communicated to several correspondents, as was also the structure throughout of the mandible of *Trimerorhachis*, with the exception of the sutures separating the anterior coronoids. Photographic copies of the figures of the mandible of this genus, as published by me in a preliminary paper in the October-November (1913) number of the *Journal of Geology*,

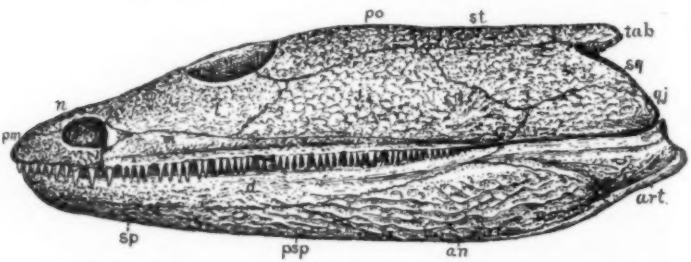


FIG. 19.—*Trimerorhachis insignis* Cope: Skull, from the side, one-half natural size. Explanations as in previous illustrations.

were distributed to various correspondents in September and October. That figure differs from the ones here shown only in the less precise sutural line between the coronoid and prearticular, and in the absence of the sutures between the anterior coronoids. All these corrections were definitely and positively recognized by me in a later collection of material sent me by Mr. Lawrence Baker in October a short time before the publication of the paper by Dr. Broom. From this it results that I had discovered the postsplenial and had suggested that name for it before Dr. Broom began his studies of the mandible; and that Dr. Broom discovered the two anterior coronoid elements before I did. The names then, postsplenial, intercoronoid, and precoronoid, may properly be retained for the new elements, provided that nowhere

in the ichthyological literature there are prior names for these elements in the crossopterygian fishes.

Although there has been an unnecessary duplication of studies which might have been avoided, the results are fortunate in their independent corroboration, placing at rest any doubts as to the real structure of the stegocephalian mandible. Dr. Broom's figures are inaccurate in detail, as will be seen by comparing them with those herewith given.

A detailed description of the elements is unnecessary; the illustrations will explain them better. In none of the many specimens have the sutures between articular and surangular been distinguished. I have spent much time in making sections of the articular end and in corroding with acid many specimens, but wholly in vain. There are certain variations in different specimens which it may be well to notice. The posterior inframeckelian foramen is sometimes situated farther in advance, and is almost wholly bordered above and below by the postsplenial. The splenial usually enters very distinctly into the mandibular symphysis; in some specimens it takes only a slight part. A structure like that of *Trimerorhachis* I have observed in *Eryops*, *Diplocaulus*, and other stegocephalians. I also find the postsplenial in *Anaschisma*, but have not distinguished the anterior coronoids.

## SUMMARY

The mandible of the primitive amphibians differs chiefly from that of the early reptiles in the division of the coronoid into three elements, or possibly four, and in the division of the splenial into two. The surangular cannot be distinguished, if present.

# *STUDIES FOR STUDENTS*

## A CLASSIFICATION OF COMMON SEDIMENTS AND SOME CRITERIA FOR IDENTIFICATION OF THE VARIOUS CLASSES

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State University of Iowa

Sedimentary rocks are useful to the geologist chiefly through the record of the history of the earth which they contain, and it is desirable that classifications of these rocks should be so arranged as to bring out as much of that history as possible. The common classification of sedimentary rocks, on the basis of texture and mineral composition, into conglomerates, sandstones, shales, and limestones is hardly adequate, because the origin of the rock is only slightly implied, if at all, in the definition. For instance, under the present classification, sandstone is sand cemented; but the discovery of sandstone in a locality may record either a shallow sea not far from shore, dry, windy conditions and the piling-up of sand by wind, the previous existence of lakes receiving sand from near-by lands, or fluvial conditions under which the sand was deposited by streams. Similarly, conglomerate may be marine, fluvial, pluvial, glacial, or lacustrine in its origin. Even limestone is being laid in inland lakes today, as well as in the sea, and by wind in the Bermuda Islands.

If sedimentary rocks are to perform their function as true recorders of past events, their classification must be based on the origin of those rocks. The agents and processes by which sedimentary rocks are made lie chiefly in the realm of physiographic geology. This paper places a physiographic interpretation on the origin of sedimentary rocks.

It is of course understood that there is a wide gap between sediments and sedimentary rocks, but it is also believed that a classification of the various sorts of sediments will be at least a step toward a more effective classification of sedimentary rocks, and

that many of the criteria for distinguishing various sorts of sediments are also applicable to rocks resulting from sediments after cementation.

The classification and lists of characters which follow are not presented with the idea that they contain matter which is new, but merely to bring together, in a way intended to be helpful, certain things which have been well known to geologists. Much of it has been published in one place and another in standard works, and these sources have been drawn upon freely in the preparation of the present paper.

The various sorts of common sediments are as follows:

Eolian
Fluvial
Pluvial
Talus
Glacial
  *a*) Till
  *b*) Fluvio-glacial deposits
Lacustrine
  *a*) Near-shore phase
  *b*) Still-water phase
Marine
  *a*) Shallow-water deposits
    (1) Zone of major agitation
    (2) Zone of minor agitation
  *b*) Deep-water deposits

By pluvial deposits are meant those transported by rain water or immediate run-off, without the agency of permanent streams. Talus deposits are those whose constituents are rolled down steep slopes by the action of gravity, not necessarily aided by water. Near-shore lacustrine deposits are those laid in lakes between high-water mark and the surf line. Shallow-water marine deposits are those laid in the sea between high-water mark and the 100-fathom line, and deep-water deposits are laid in the deep sea beyond the 100-fathom line. The shallow-water deposits of the sea have been generally divided into (*a*) littoral deposits (those laid between high- and low-water marks) and (*b*) non-littoral deposits (between low-water mark and the 100-fathom line).[1] For present purposes

[1] See Murray, *Report of the H.M.S. Challenger, Deep Sea Deposits*, p. 186; and Chamberlin and Salisbury, *Geology*, I, 368, 369, and 379.

at least this is not a happy division, for after analysis it is clear that the differences between deposits above low-water mark and those below low-water mark are slight, and that the differences between deposits in greatly agitated waters and those in quieter waters are great. In spite of infelicities of expression, it seems best here to divide the shallow-water deposits of the sea into two groups, (*a*) those of the zone of major agitation, and (*b*) those of the zone of minor agitation. The deposits of the zone of major agitation include beach deposits, bars, spits, hooks, barrier reefs, etc., for the most part materials laid within the surf line, and the deposits of minor agitation are those laid in quieter water in general beyond the surf line. None of the other terms needs definition here.

The lists of characters of these various sorts of deposits, given below, are the results of (1) a study of the processes and agents by which they are deposited, and (2) observation of undoubted types of the various sorts of deposits in the field. Sand dunes have been studied at the south end of Lake Michigan and loess in Iowa, Illinois, and Wisconsin. Fluvial deposits were examined particularly in Owens Valley, California. Pluvial deposits were noted in Owens Valley, and in the southern Appalachians; talus slopes in Wisconsin, California, and Wyoming; glacial materials in Wisconsin and Illinois; lacustrine deposits in extinct lake bottoms in Wisconsin, and in the Pliocene lake deposits of the Inyo Mountains; and marine deposits in the Paleozoic rocks of the Mississippi Valley.

### CHARACTERS OF EOLIAN DEPOSITS

Eolian deposits have the following characteristics. For the sake of brevity they are listed.

1. Low textural range.
2. Material all finely divided.
3. Sorted into irregular beds and lenses.
4. Stratification-planes dip in all directions.
5. Stratification-planes have dips varying in amount up to 30° ±.
6. Material porous.
7. Distributed in irregular areas, not continuous.
8. Vary greatly in thickness within short distances.
9. May be ripple-marked.
10. Grains of sand are rounded.
11. Fossils, if any, are of terrestrial forms.

Most of the foregoing statements need no explanation. No. 4 is due to the constant shifting of the wind and to the irregular surfaces on which dust and sand are laid. In No. 5, the 30° dip is the angle of the lee-sides of sand dunes, as read with the clinometer, and is the angle of rest for sand. These are the characters of eolian sand, but, with the possible exception of 5, 7, 9, and 10, they also characterize loess. A typical section of dune sand is shown in Fig. 1.

FIG. 1.—A section of sand deposited by the wind near Cape Henry, Virginia (photograph by Dr. T. W. Vaughan).

### CHARACTERS OF FLUVIAL DEPOSITS

The conditions under which streams deposit are so various that it is difficult and perhaps unwise to list any one set of characters which will fit all fluvial materials. Swift streams deposit their coarse loads at the bases of mountains under conditions quite different from those of larger and sluggish streams depositing on their flood plains, and yet both distribute, both flow in one general direction, both sort their materials at least roughly, and, after all, the results differ chiefly in degree rather than in principle. Fluvial deposits have the following characteristics:

1. Relatively fine material, though some fans include large bowlders.
2. High textural range (fans), and low textural range (some flood-plain deposits).
3. Only roughly sorted.
4. Lens and pocket structure.

5. Distributed in belts (river flats and piedmont alluvial plains).

6. Bedding planes dip in one general direction, though slightly divergent in the direction of general dip.

7. Beds dip at angles varying up to 18°±.

8. Deposit diminishes uniformly in thickness in the direction of the divergence of dips.

9. Material likely to be heterogeneous, lithologically.

10. Pieces angular or rounded.

11. Fossils rare, and of terrestrial forms.

FIG. 2.—A typical fluvial deposit, showing lens and pocket structure. A section of a stream terrace in Jo Daviess County, Ill.

The lens and pocket structure seems to be especially characteristic of fluvial deposits. In Owens Valley no textural division in the fans could be traced more than fifty feet in any direction. This structure is quite unlike the layered character of still-water deposits such as those laid in lakes or in the sea, and somewhat different from the structure of materials deposited by ocean or lake waves and currents. The 18° of No. 7 above is the highest angle read on the surface of the fans. The slight divergence of dips as stated in No. 6 is due to distribution of the streams. Fig. 2

shows a fluvial deposit of one type in a stream terrace in northwestern Illinois. Lens and pocket structure is visible here. A somewhat different type is shown in Fig. 3, this being a photograph of a section of an alluvial fan at the foot of the Sierra Nevada Mountains in California. While these two deposits are quite different, the differences are those of degree rather than of principle.

FIG. 3.—A fluvial deposit at the foot of the Sierra Nevada Mountains in California.

### CHARACTERS OF PLUVIAL DEPOSITS

Pluvial deposits are similar to those deposited under fluvial conditions, except that (1) the material is not so well sorted, (2) it is more restricted in distribution, (3) the beds, if any, dip at higher angles, (4) the material is more likely to be homogeneous lithologically, for it has not been transported so far from the parent ledges, and (5), because not transported so far, the constituent pieces are likely to be more angular. For the sake of easy reference, the list of characters follows:

1. Material coarse.
2. High textural range.

FIG. 4.—A pluvial deposit in North Carolina.

FIG. 5.—A pluvial deposit at the foot of the Inyo Mountains in California. The crude sorting and the angularity of the pieces are the features of the section.

3. Very crude sorting.
4. Distributed in restricted areas, on or near steep slopes.
5. Beds, if any are visible, dip in one general direction, though diverging.
6. Beds, if any, may dip at high angles.
7. Deposit varies in thickness, decreasing uniformly in direction of divergence of dips.
8. Material local and homogeneous lithologically.
9. Pieces, angular.
10. Fossils, if any, of terrestrial forms.
11. Surface and base of formation may have steep slopes.

Figs. 4 and 5 show types of pluvial deposits, one in North Carolina and the other at the foot of the Inyo Mountains in California.

### CHARACTERS OF TALUS DEPOSITS

Talus deposits are not abundant among sedimentary materials, and yet they exist. At Ableman, Wis., a talus slope of Huronian quartzite is included in Potsdam sandstone, and it is possible that other conglomerates belong to this type of deposits. The characters of these deposits are listed below. Fig. 6 shows a talus slope of quartzite at Devils Lake, Wis.

1. Coarse material greatly predominates over fine.
2. Pieces are the result of mechanical disintegration.
3. Pieces angular.
4. No stratification.
5. Distributed in restricted and isolated areas, or in very narrow belts near high lands.
6. Base and surface of formation have steep slopes.
7. Pieces touch one another.
8. Very porous.

### CHARACTERS OF GLACIAL TILL

The characters of glacial till are so well known as to need no discussion here. For the sake of getting the criteria together the list is given.

1. Heterogeneous in composition.
2. High textural range (rock flour to enormous bowlders).
3. Coarse material generally subordinate in amount to fine.
4. No stratification.
5. Constituents, largely subangular.
6. Great variation in thickness within short distances.

FIG. 6.—A talus slope of blocks of quartzite at Devils Lake, Wis. (photograph by J. J. Runner).

7. Appreciable part of material foreign to location in which deposit is found (does not hold for all glacial deposits in high mountains).
8. Some of the stony matter striated.
9. Lies on unweathered bed (in general).
10. Sharp plane between drift and underlying formation.
11. Beds striated, grooved, bruised, etc.
12. Fossils, if any, show evidences of wear by transportation.

This type of deposit is illustrated in Fig. 7.

FIG. 7.—A section of glacial till in Wisconsin.

### CHARACTERS OF FLUVIO-GLACIAL DEPOSITS

Corresponding with the characters of the depositing agents, fluvio-glacial deposits are closely allied to fluvial deposits on the one hand and to glacial till on the other; in general they resemble the former in texture and the latter in lithologic constitution. In shape the constituents of these deposits are a combination of form due to glacial wear and that given to pieces rolled along the bottoms of streams. The list follows:

1. Heterogeneous in constitution.
2. Moderate textural range.
3. All material stratified.

4. Sorted into lenses and pockets rather than into definite, uniform, continuous layers.

5. Constituents have a roundness superimposed on subangularity.

6. Striae rare or lacking on pebbles.

7. Thickness varies with irregularities in bed and shows a general tendency to thin in one direction.

8. Appreciable part of material foreign.

9. Generally does not lie on bed rock, and contact below is not necessarily sharp.

10. Fossils worn, but may include unworn terrestrial forms.

11. Likely to be found in the vicinity of glacial till.

FIG. 8.—A fluvio-glacial deposit in Wisconsin (photograph by L. E. Wells).

Fluvio-glacial deposits bear all relations in position to glacial till. They lie over, under, or within the till, though they may also lie out beyond the till in the form of outwash plains or valley trains. Fluvio-glacial deposits are shown photographically in Fig. 8.

### LACUSTRINE DEPOSITS (NEAR-SHORE PHASE)

In these deposits are the materials brought to lakes by streams, cut from the shores by waves, carried and deposited by feeble littoral currents, etc. The zone of deposition is one of frequently changing conditions, due to changes in volume of streams, strength of wind, direction of shore currents, shape of spits, bars, deltas, etc. These deposits may be distinguished by the following characters:

1. Material likely to be coarse.
2. High textural range (bowlders to silt).
3. Well sorted into lenses and pockets and arranged in linear areas.
4. Textural divisions grade out in all directions.
5. Fossils from running-water, surf-water, and still-water habitats.
6. Constituents well or poorly flattened.
7. Cross-bedded.
8. Special markings; ripple-, wave-, rill-marks, mud-cracks.
9. Rather abrupt variations in thickness.
10. Bedding planes dip in all directions, predominantly from shore.
11. Bedding planes dip at angles varying up to angle of rest for the materials (edges of deltas, ends of spits, etc.).
12. Distributed in narrow belt parallel with lake shore.

FIG. 9.—A near-shore phase of lacustrine deposit in Wisconsin.

Fig 9 shows some lacustrine sand and gravel exposed in the margin of the bottom of an extinct lake in Wisconsin.

LACUSTRINE DEPOSITS (STILL-WATER PHASE)

1. Material fine in texture.
2. Low textural range (sand to silt).
3. Well sorted into definite layers.
4. Rather uniform in thickness.
5. Beds likely to be finely laminated (in some cases 20 to the inch).
6. Distributed continuously over large or small areas, according to size of depositing lake.

7. Surrounded by near-shore lacustrine deposits.
8. Textural divisions grade into one another vertically, but not laterally.
9. Fossils of still-water types of life.
10. Bedding planes essentially horizontal.
11. May be ripple-marked.

Fig. 10 shows a section of laminated lake clays which were found less than half a mile from the section in Fig. 9. Fig. 10 illustrates the still-water phase of lacustrine deposits as contrasted with the near-shore phase deposited in the same lake. Another contrast of this sort may be seen in Figs. 14 and 15, *Jour. Geol.*, XIX, 724.

### SHALLOW-WATER MARINE DEPOSITS

#### ZONE OF MAJOR AGITATION

1. In general coarse material.
2. Rather high textural range (bowlders to mud).
3. Sorted into lenses, pockets, irregular linear areas.
4. Contain marine fossils with possible mixture of land forms.
5. Distributed in rather narrow belt parallel with coast.
6. Different textural divisions grade out laterally and vertically.
7. Special markings; ripple-, rill-, wave-marks, mud-cracks.
8. Sorted texturally and to some extent mineralogically.
9. Considerable range in thickness within short distances.
10. Cross-bedded.
11. Constituents likely to be flattened.
12. Bedding planes dip in all directions, but chiefly from shore.
13. Bedding planes have dips varying up to angle of rest for the materials (edges of deltas, ends of spits, etc.).

By comparing these characters with those of the near-shore phase of the lacustrine deposits, these two sorts of deposits are found to have the same characters, with the exception of fossils and a slight difference in distribution. There would also be a difference in degree; that is, the marine deposits might contain coarser material, have a higher textural range, thicker textural divisions, etc. This type of sediment after cementation is illustrated in Fig. 11 which shows a section in the Potsdam sandstone at the Dells of the Wisconsin River near Kilbourn, Wis.

FIG. 10.—Some laminated lake clays deposited in the still water of the same lake which received the near-shore deposits of Fig. 9.

FIG. 11.—The Potsdam sandstone, a type of deposits in the sea in the zone of major agitation.

### SHALLOW-WATER MARINE DEPOSITS

#### ZONE OF MINOR AGITATION

There is no great difference between these materials and the still-water lacustrine deposits, though there are differences in distribution, fossils, textural range, texture, etc. The list follows:

1. Average materials fine in texture.
2. Rather low textural range (sand to silt and limestone).
3. Sorted into definite continuous layers.

FIG. 12.—A section in the Galena dolomite of northwestern Illinois. This is a shallow-water marine deposit in the zone of minor agitation.

4. Marine fossils.
5. Distributed continuously over wide areas.
6. Does not vary greatly in thickness within short distances.
7. Special markings; ripple-marks (not rill- or wave-marks, or mud-cracks).
8. Include chemical and organic deposits.
9. Bedding planes essentially horizontal.

This deposit is well illustrated by the Galena dolomite of northwestern Illinois, which is shown in Fig. 12. All the essential

## KEY TABLE FOR IDENTIFICATION OF VARIOUS CLASSES OF SEDIMENTS

| | Eolian | Fluvial | Pluvial | Talus | Glacial Till |
|---|---|---|---|---|---|
| Texture | Fine | Variable | Coarse | Coarse | Variable |
| Textural range | Low | High | High | Medium | Very high |
| Stratification | Irregular beds and lenses | Lenses and pockets | Lacking | Lacking | None |
| Constitution | Homogeneous or heterogeneous | Heterogeneous | Fairly homogeneous | Homogeneous | Heterogeneous, including foreign matter |
| Distribution | Irregular areas, not continuous | In narrow, linear areas | Restricted, isolated areas | Restricted, isolated areas | Broad areas |
| Amount of dip | Variable within limits (0–30°) | Variable within limits (0–18°) | ..... | ..... | ..... |
| Direction of dip | In all directions | Diverge in one general direction | ..... | ..... | ..... |
| Thickness | Varies greatly in short distances | Decrease uniformly in one direction | Increases in one direction | Variable | Exceedingly variable |
| Shape of pieces | Rounded, pitted | Angular or rounded | Angular | Angular | Subangular, striated |
| Fossils | Land forms suggesting aridity | Fresh-water and land forms (scarce) | Terrestrial forms, if any | ..... | Terrestrial or marine forms but worn |
| Characters not included above | May be ripple-marked | May include large bowlders | Found only near highlands | Very porous | Lie on unweathered, striated bed. Large bowlders |

| | Fluvio-glacial | Lacustrine (Near-Shore Phase) | Lacustrine (Still-Water Phase) | Shallow-Water Marine (Zone of Major Agitation) | Shallow-Water Marine (Zone of Minor Agitation) |
|---|---|---|---|---|---|
| Texture | Medium | Variable | Fine | Coarse | Fine |
| Textural range | Rather low | Rather high | Low | High | Low |
| Stratification | Lenses and pockets | Lenses, pockets, belts | Layered, laminated | Lenses, pockets, belts | Definite, continuous layers |
| Constitution | Heterogeneous | ..... | ..... | Heterogeneous | Mechanical, chemical, and organic deposits |
| Distribution | In belts | Belts | Over more or less wide areas | Long, continuous belts | Continuous over wide areas |
| Amount of dip | Cross-beds may have high dips | Variable within limits | Essentially horizontal | Variable within limits | Essentially horizontal |
| Direction of dip | Diverge in one direction | In all directions, chiefly from shore | ..... | In all directions, especially from shore | ..... |
| Thickness | Decrease in one direction | Variable | Uniform | Variable | Uniform |
| Shape of pieces | Roundness on subangularity | Flattened or rounded | ..... | Flattened or rounded | ..... |
| Fossils | Terrestrial, worn if marine | Fresh-water forms (running-, surf-, and still-water) | Fresh-water forms (still-water) | Marine, with possible land forms | Marine forms |
| Characters not included above | Occur near till | Cross-bedding, ripple-, wave-, rill-marks, mud-cracks | Laminae | Cross-bedding, ripple-, wave-, rill-marks, mud-cracks | Possible ripple-marks |

characters have been retained even after cementation and partial metamorphism.

### DEEP-WATER MARINE DEPOSITS

Deposits of the deep sea, that is, those materials laid in the sea beyond the edge of the continental shelf, are not here described, partly because their position of deposition makes their study in place almost impossible and partly because they are not commonly represented on the lands either in cemented or unconsolidated rocks. They are known, however, to consist of the finest terrigenous material, remains of pelagic life, submarine volcanic materials, atmospheric dust, extra-terrestrial materials, and the results of chemical alteration of the above-mentioned substances. Presumably most of it is finely divided, has a low textural range, and lies in horizontal strata. The fossils are doubtless pelagic in character.

An attempt is made to condense all the important characters in the foregoing lists into a single table which may be used as a key to the identification of the various common sediments.

Lacroix, A. "Les roches grenues, intrusives dans les brèches basaltiques de la Réunion: leur importance pour l'interprétation de l'origine des enclaves homéogènes des roches volcaniques," *Comptes rendus*, CLIV, No. 10 (1912), pp. 630–35.

Basaltic breccias on the island of Reunion, about 300 miles east of Madagascar, are cut by dikes and sills of syenite, gabbro, and peridotite, clearly exposed in mountain amphitheaters.

The prevailing type of syenite consists for the most part of various alkali-feldspars, accompanied by alkaline pyroxenes and amphiboles. A scarcer variety contains biotite and a little plagioclase. The gabbros vary in composition: some contain both augite and olivine; those with olivine alone pass to a variety with very basic plagioclase and finally to peridotite; some of the gabbro is essexitic in character. The peridotite is chiefly dunite, but this passes to wehrlite by addition of diopside. The most basic of the intrusives are the oldest. Their chemical relation to the volcanic rocks is not known, except that some of the gabbro is almost identical in composition with some of the basalt.

This occurrence affords a striking proof that coarsely granular rocks have solidified at a depth of only a few hundred meters, in volcanic rocks of Tertiary—probably late Tertiary—age. The author infers that the influence of depth on crystallization has been greatly exaggerated, and that, while a thick cover may be favorable, it is by no means essential to the development of granular texture. He believes that granular rocks may be crystallizing at the present time in the flanks of active volcanoes. In the Reunion locality, he sees no confirmation of Harker's hypothesis that the normal order of igneous manifestations is: (1) volcanic action, (2) plutonic intrusions, (3) small intrusions. He considers the volcanic rocks and the small intrusions contemporaneous.

The author also sees in this locality a demonstration that certain "homogeneous inclusions" in volcanic rocks have been formed by differentiation of the magma prior to eruption, with the result that distinct geologic bodies are formed, fragments of which are loosened and brought to the surface by the ascending lava.

F. C. Calkins

LACROIX, A. *Discours prononcé a la séance de clôture du congrès.* Congrès des Sociétés Savantes à Paris, 1912. Pp. 20.

A study of the volcanoes of Madagascar.

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LACROIX, A. "Sur la constitution minéralogique des volcans de l'île de la Réunion," *Comptes rendus*, CLV (1912), 538–44.

From a single volcano and a single magma there have been erupted subalkaline and alkaline rocks, rocks which had long been considered as necessarily having independent origins and localized in distinct regions of the world (Atlantic and Pacific provinces). Nineteen analyses are given.

A. J.

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LACROIX, A. "Un voyage au pays des Béryls (Madagascar). La Géographie," *Bull. Soc. Geog.*, XXVI (1912), 285–96.

A popular account of the minerals of Madagascar.

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LACROIX, A. *Les richesses minérales de Madagascar.* Conférence faite à l'Ecole Coloniale le 22 Déc., 1912. Paris, 1913. Pp. 10.

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LEISS, C. "Ueber zwei neue Mikroskope für petrographische und krystalloptische Studien," *Zeitschr. f. Kryst.*, XLIX (1911).

Describes two new microscopes with nicol prisms connected by a rigid bar. The first is after de Souza-Brandão and was originally described and illustrated in 1903 in the report of the geological survey of Portugal. Besides the attachments usual in a large petrographic microscope, this instrument has a stage which may be tilted to any angle, and an Abbe illuminating apparatus. The second, with a similar bar connection, is after Wright, and was first described in 1910. In this, likewise, the illuminating apparatus is after Abbe. A compensator ocular is permanently attached to the tube.

A. J.

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LEISS, C. "Neues petrographisches Mikroskop für die Theodolit-Methode," *Centralbl. f. Min., etc.*, 1912, 733–36.

Describes a microscope which combines in itself a von Fedorow stage and a petrographic microscope with simultaneously rotating nicols.

The universal stage in this instrument, however, is considerably larger than in the detachable stage, being capable of taking sections 28×48 mm., thus doing away with the necessity of using circular sections.

A. J.

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LOEWINSON-LESSING, F. "Beiträge zur Systematik der Eruptivgesteine, I." *Tiré d. Ann. d. Inst. Polyt. Pierre le Grand a St. Pétersbourg*, XV (1911), 229–43.

After a period of ten years, the author resumes his critical studies on the nomenclature and classification of igneous rocks, and proposes to issue a continuation of his former series of papers which was published in *Tschermak's Miltheilungen* in 1889–1902. The paper here reviewed is the first of the new series, unfortunately printed in the Russian language and consequently unavailable, except so far as the short résumé in German goes, to the majority of the petrologists in this country.

The writer discusses first the transition members of the effusive rocks between those from the alkali and from the alkali-earth magmas, and second, the absence of mono-mineral rocks among the effusives. He believes this absence to be a proof that the formation of eutectic and mono-mineral differentiation rocks takes place only in deep-seated magmas. That they do not reach the surface as effusives he thinks may be due to their viscosity and high melting-point, or that they are more active in assimilating the country rocks and, therefore, in the course of their eruption, always become changed in composition.

ALBERT JOHANNSEN

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LOUDERBACK, GEORGE DAVIS. "The Monterey Series in California," *Bull. Dept. Geol. Univ. Cal.*, VII (1913), 177–241.

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LOUGHLIN, G. F. "Contribution to the Geology of the Boston and Norfolk Basins, Massachusetts. I. The Structural Relations between the Quincy Granite and the Adjacent Sedimentary Formations," *Amer. Jour. Sci.*, XXXII (1911), 17–32.

The igneous rocks in the area studied include an altered biotite granite series, an older felsite series, the Quincy alkaline granite series, and alkaline felsite. The sediments are much folded and include the conglomerates, sandstones, and slates of the Boston and Norfolk basins.

A. J.

# *Reviews*

"The Stability Relations of the Silica Minerals." By CLARENCE N. FENNER. *Am. Jour. Sci.*, Ser. IV. Vol. XXXVI (1913), pp. 331–84, fig. 9.

A report of the results of a rigorous study of the various polymorphous modifications of silica. The work shows conclusively that the relations between quartz, tridymite, and cristobalite are enantiotropic. New determinations of the inversion points, including those between $\alpha$ and $\beta$ phases of quartz, tridymite, and cristobalite, are given. The paper represents by far the most exact work upon the subject to date, and is made especially valuable by carefully constructed diagrams showing the relations between the various phases.

A. D. B.

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*The Mount Grainger Goldfield.* By R. LOCKHART JACK. Report No. 2, Geol. Surv. of So. Australia. Adelaide, 1913. Pp. 24, figs. 10, pl. 1.

Describes very briefly the chief structural features of the region and the more important workings.

A. D. B.